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SOME TUNNELING STUDIES IN NORMAL
METAL-INSULATOR-METAL JUNCTIONS

by



JOZEF STRAUS

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
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The undersigned certify that they have read,
and recommend to the Faculty of Graduate Studies and
Research, for acceptance, a thesis entitled SOME TUNNELING
STUDIES IN NORMAL METAL-INSULATOR-METAL JUNCTIONS submitted
by Josef Straus in partial fulfillment of the requirements
for the degree of Doctor of Philosophy.

TO MY LOVING PARENTS

ABSTRACT

A theory (Trofimenkoff, et al, 1972) of a non-equilibrium electron tunneling in normal metal-insulator-metal junctions has been proposed to explain the presence of a small ($\sim 1\%$) conductance reduction around zero bias. In particular, the related structure in σ and $d\sigma/dV$ have been accounted for by the blocking of otherwise available electron states due to finite electron relaxation times in metal electrodes. Detailed measurements on Mg/Mg, Mg/Au and Al/Al junctions have been performed and the results compared with predictions of the theory. In all cases a satisfactory agreement between the theory and the experiment was found. The inclusion of non-equilibrium phonons in metal electrodes has been suggested as a further refinement of the theory.

Measurements on some Mg/Mg and Mg/Au junctions have shown an additional oscillatory type structure in the derivative of the conductance. The occurrence of the structure has been found to be independent of metal electrodes, and barrier layers. Under the influence of external perturbations such as warming the junctions to room temperature, applying DC bias up to 1 eV and passing currents along the metal electrodes, the properties of the junctions were irreversibly altered. This suggests that impurity contamination of

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the barrier is responsible for the observed structure.

Tunneling experiments have been performed in an attempt to observe the quantization of allowed energy levels in Bi films. The structure in Bi/Bi junctions, however, could not be correlated with the film thickness, thus rendering the results negative. As a byproduct of the investigation, a phonon spectrum of Bi has been determined.

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THEORY

The first part of the paper is devoted to a review of the literature on the effects of the environment on the development of the child. The second part is devoted to a review of the literature on the effects of the environment on the development of the adult. The third part is devoted to a review of the literature on the effects of the environment on the development of the elderly.

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Finally, I am thankful to Mrs. Mary Yiu for her patience and excellent typing performance of this thesis.

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CHAPTER 1

THEORETICAL DISCUSSION

1.1 Introduction

The concept of a particle tunneling from a classically allowed region of space through a classically forbidden region, into the second allowed region was one of the early predictions of Schrödinger's wave equation.

The possibility that a tunnel current may flow between metals separated by a vacuum was first considered by Frenkel (Frenkel, 1930). Sommerfeld and Bethe (Sommerfeld and Bethe, 1933) extended Frenkel's calculation to the case in which the vacuum was replaced by a thin insulating layer. The actual physical fabrication of such a system was delayed until 1960 when the thin film technology had sufficiently advanced allowing Fisher and Giaver (Fisher, Giaver, 1961) to build a tunnel structure using aluminum-aluminum-oxide-aluminum. The results of their experiments stimulated a sequence of measurements on both normal and superconducting tunnel junctions with far reaching results leading to a better understanding of electron transport phenomena in metals.

1.2 Theory of elastic tunneling

Bardeen (Bardeen, 1961) has regarded the tunneling

process as a transition of an electron across the barrier which itself acts as a perturbing potential. The composite metal-insulator-metal system is described by Hamiltonians H_1 , H_2 of the left and right hand metals and one electron eigenstates ψ_1 and ψ_2 which are weakly coupled together by a perturbation U (fig.1.1). By taking a linear combination of ψ_1 and ψ_2 we seek then a modified solution to the time dependent Schrödinger equation. Knowing ψ_1 and ψ_2 the transition matrix element M_{12} of the Hamiltonian between states ψ_1 and ψ_2 can then be calculated using the method of time dependent perturbation theory.

The transition probability P_{12} per unit time of an electron in a state ψ_1 to a state ψ_2 is then given by Fermi golden rule

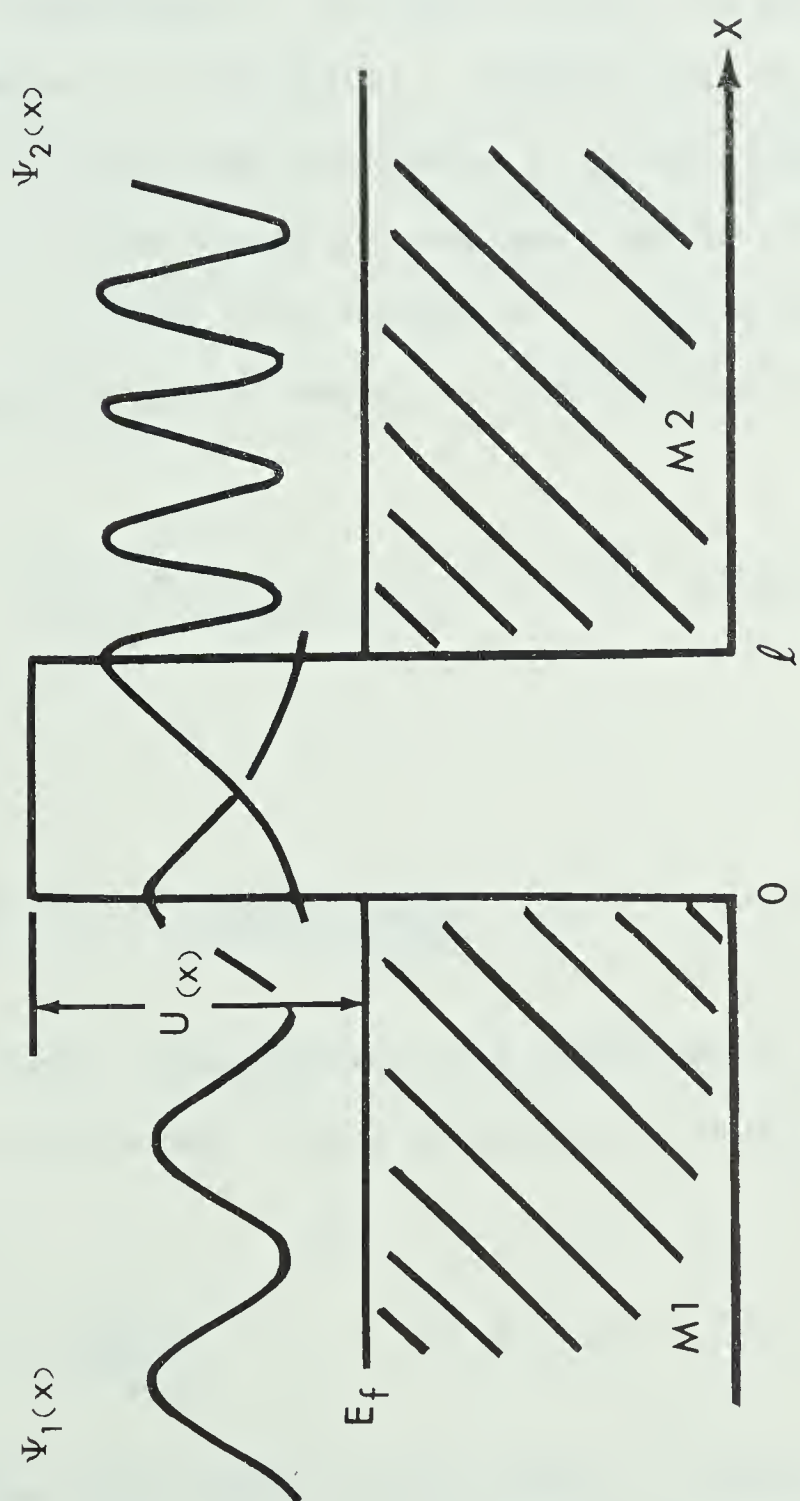
$$P_{12} = \frac{2\pi}{\hbar} |M_{12}|^2 \rho_2 f_1^0 (1 - f_2^0) \quad (1.1)$$

where ρ_2 is the density of final states in the metal 2, f_1^0 and f_2^0 are the Fermi-Dirac probabilities of occupation of states ψ_1 and ψ_2 .

As an approximation for the electron current density between the two metals, an independent particle model is used. It is assumed that the metal-insulator interface is planar and that the component of the wave number parallel to the plane of the barrier, $k_{||}$, is

Fig. 1.1

Transfer Hamiltonian Model



conserved before and after the transmission. The total energy of the electron of course, is conserved and this is implied when writing eq. (1.1). To obtain the tunneling current from metal 1 to metal 2, P_{12} is summed over all states 1 of fixed $k_{||}$, summed over $k_{||}$, multiplied by 2 for spin and by charge e of the electron. The sum over states 1 may be replaced by an integral over energy at fixed wave number $k_{||}$. Subtracting the current from metal 2 to metal 1, one obtains for the net current

$$I = \frac{4\pi e}{\hbar} \sum_{k_{||}} \int_0^{\infty} |M_{12}|^2 \rho_1(E_x) \rho_2(E_x + eV) [f^0(E) - f^0(E + eV)] dE_x \quad (1.2)$$

where

$$f^0(E) = \frac{1}{1 + e^{(E - E_{f1})/K_B T}}$$

and ρ_i , $i = 1, 2$, represents a one dimensional density of states, associated with the motion perpendicular to the barrier

$$\rho_i = \frac{L}{\pi} \left(\frac{\partial E}{\partial k_{x_i}} \right)^{-1} \quad i = 1, 2 \quad (1.3)$$

where L gives the length of the metal. Unless otherwise stated all energies are measured with reference to the bottom of the conduction band of metal 1. Because of the independent particle model, we can write E as

$$E = E_x + E_{||}$$

with

$$E_{||} = \frac{\hbar^2 k_{||}^2}{2m}, \quad E_x = \frac{\hbar^2 k_x^2}{2m}.$$

The functional form of the matrix element $|M_{12}|^2$ depends on the profile of the barrier potential used for the calculation of electron transmission probability. Harison, (Harrison, 1961) applying a WKB approximation found that

$$|M_{12}|^2 = \frac{D(E, E_{||})}{4\pi^2 \rho_1 \rho_2} \quad (1.4)$$

where the barrier transmission coefficient D is given by

$$D(E, E_{||}) = \exp\left(-2 \int_0^{\ell} \sqrt{\frac{2m}{\hbar^2} (U(x) - (E - E_{||}))} dx\right). \quad (1.5)$$

Substituting eq. (1.4) for $|M_{12}|^2$ into eq. (1.2) we obtain

$$I = \frac{2e}{\hbar} \sum_{k_{||}} \int_0^{\infty} D(E, E_{||}) (f^0(E) - f^0(E + eV)) dE_x \quad (1.6)$$

and find that the density of states factors appearing in eq. (1.2) have cancelled with the matrix element so that the tunneling current does not explicitly depend on them. The absence of density of states in eq. (1.6) is a result of the independent particle model, which enabled the separation of the electron wave number into

parallel and perpendicular components with respect to the plane of the barrier and the replacement of the sum over the normal components by an integral over energy E_x . Furthermore, the WKB approximation is restricted only to regions where the fractional change in the electron wavelength is small i.e. $\frac{\delta\lambda}{\lambda} \ll 1$. This is not satisfied for electrons near the band edge, having small kinetic energy. Therefore, as Harrison points out, band edges and energy gaps may introduce an observable structure in the tunneling current.

The form of the matrix element eq. (1.3) and its use in eq. (1.5) implies that the tunneling is from one quasi-continuous band of states, through the barrier into another quasi-continuous band. If, on the other hand, ρ_2 is a set of localized surface states or impurity states, the resulting matrix element is no longer proportional to ρ_2^{-1} but rather to τ^{-1} , the lifetime of the state (Penley, 1962), and the density of such states does not cancel. In general, if the rate limiting quantity in the tunneling process is the electron velocity, and if the velocity is inversely proportional to the density of states, which is characteristic of a band of single particle states, then the tunneling current does not contain information about the density of states. But, if the tunneling process is primarily via traps and defect states in

the insulator, which can be characterized by a lifetime τ , the density of states should not cancel.

Eq. (1.6) can be cast into a more convenient form by converting the sum over $k_{||}$ to an integral over $k_{||}$ and then to an integral over $E_{||}$, with

$$d^2k_{||} = \frac{m}{2\pi\hbar^2} dE_{||}.$$

$$I = \frac{4\pi meA}{h^3} \int_0^\infty \int_0^\infty [f^0(E) - f^0(E + eV)] D(E, E_{||}) dE_x dE_{||}. \quad (1.7)$$

The upper limit on the integration over $dE_{||}$ can be determined from the condition that the component of the wave number parallel to the plane of the barrier $k_{||}$ and the electron energy E are conserved during transition. Exchanging the order of integration in eq. (1.7) and noting that $D(E, E_{||}) = D(E_x)$ and $\partial E_{||} / \partial E = 1$ we obtain

$$I = \frac{4\pi meA}{h^3} \int_0^\infty [f^0(E) - f^0(E + eV)] dE \int_0^E D(E_x) dE_x \quad (1.8)$$

where A is the effective junction area.

For illustration, we calculate the tunneling current at $T = 0$ K. Since

$$f^0(E) - f^0(E + eV) = 0,$$

unless

$$E_{f1} - eV < E < E_{f1}$$

when

$$f^0(E) - f^0(E + eV) = 1$$

eq. (1.8) reduces to:

$$I = \frac{4\pi meA}{h^3} \int_{E_{f1}-eV}^{E_{f1}} dE \int_0^E D(E_x) dE_x \quad (1.9)$$

or

$$I = \frac{4\pi meA}{h^3} (eV) \int_0^{E_{f1}} D(E_x) dE \quad (1.10)$$

providing that $eV \ll E_{f1}$. The current is therefore ohmic at low biases. The current at $T \neq 0$ K can be connected to the current at $T = 0$ K (Stratton, 1962) by

$$\frac{I(V, T)}{I(V, 0)} = \frac{\pi C K_B T}{\sin \pi C K_B T} \quad (1.11)$$

where C is a constant dependent on the barrier height and thickness. The expected variation of the current with temperature is more apparent in eq. (1.11) (Maissel, Glang, 1970)

$$\Delta I(V, T) = \frac{I(V, T) - I(V, 0)}{I(V, 0)} = 3 \times 10^{-9} \frac{(\ell \cdot T)^2}{\phi} \quad (1.12)$$

where ℓ is in $\text{\AA}$, and T and ϕ (average barrier potential) are in conventional units. For typical parameters $\phi = 1 \text{ eV}$, $\ell = 30 \text{ \AA}$, $T = 5 \text{ K}$,

$$\Delta I(V, T) \sim 10^{-5}$$

which is negligible.

1.3 Inelastic tunneling

Tunneling which involved a loss of energy by tunneling to localized impurities in the barrier was first reported by Jacklevic and Lambe (Jacklevic and Lambe, 1966). In studying Al-insulator-Pb tunnel junctions, they have noticed increases in the conductance of the junctions at characteristic voltages corresponding to vibrational frequencies $\hbar\omega$ of molecular species contained in the insulating region of the junction. The energy level diagram on fig. 1.2 allows a visualization as to how such processes can lead to increases in conductance.

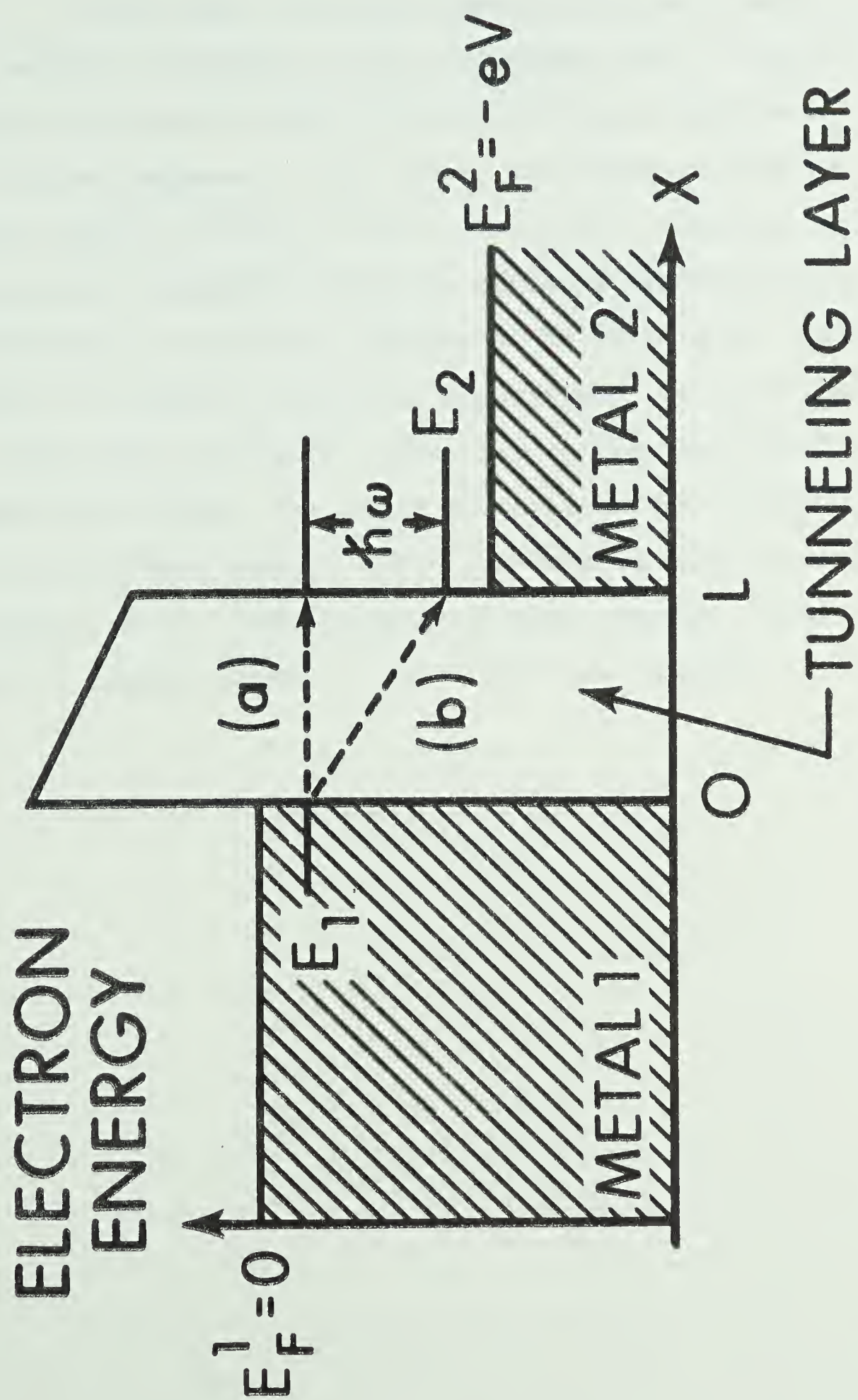
Fig. 1.2 represents a tunnel junction energy level diagram where the Fermi levels of the two metals are separated by the energy eV where V is the applied voltage. For simplicity let us assume that the system is at $T = 0$ K which means that the Fermi levels are sharp and the impurity present in the barrier is in its ground state. Electrons may tunnel elastically from metal 1 to metal 2 (process a). If a new mechanism exists so that an electron can lose energy $\hbar\omega$ to a localized impurity in the barrier as it is tunneling (process b) a new channel will open up. This new channel is possible only if there exist empty states in metal 2 at an energy $\hbar\omega$ less than E_1 . This becomes possible when $eV \geq \hbar\omega$.



Fig. 1.2

Schematic energy level diagram for
tunneling between normal metals:

- a) elastic tunneling
- b) inelastic tunneling.



This onset of a new tunneling channel results in a steplike increase in the conductance and δ function like structure in the derivative of the conductance. A finite temperature will smear the Fermi surface of both metals and thus it will smear the δ function like structure although it will be centered around $eV = \hbar\omega$. The energy loss of the tunneling electron is not limited only to losses to localized impurities. In fact, as it was shown by Giaver and Zeller (Giaver and Zeller, 1968) and others, inelastic excitations due to phonons of the barrier (Adler, 1969), phonons of metal electrode (Rowell et al, 1969) itself, surface plasmons (Tsui, 1969), magnons (Tsui, et al, 1971) are possible.

CHAPTER 2

THE ZERO BIAS ANOMALY

2.1 Introduction

The description of a tunnel junction at small biases ($eV \ll \phi$) as an ohmic element (eq. 1.10) is found to be adequate only when analyzing I-V curves. Conductance measurements using derivative techniques to an accuracy of $\sim 1\%$ have shown that the conductance of a tunnel junction up to 500 meV is roughly parabolic

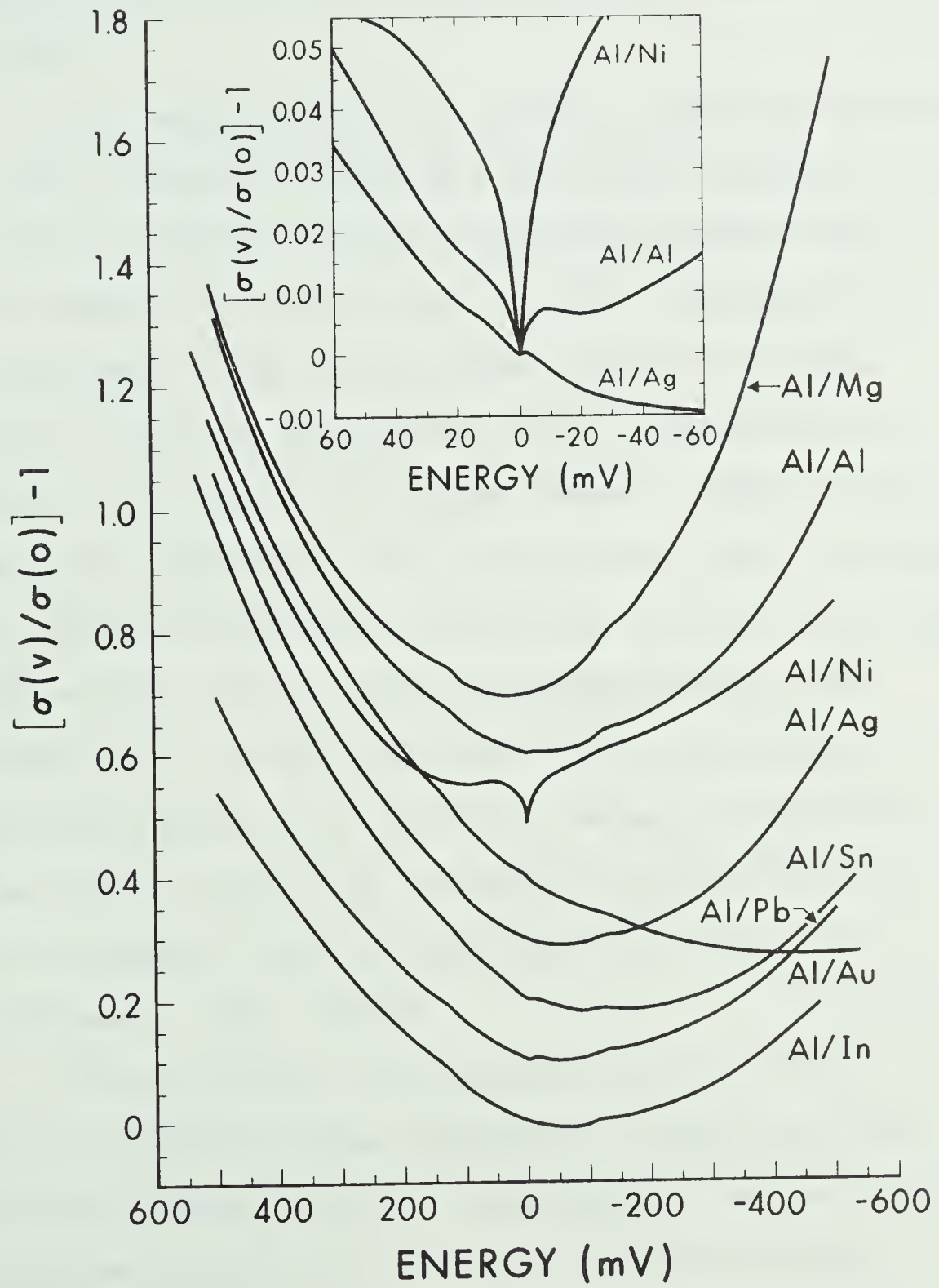
$$\sigma(V) = \alpha + \beta V + \gamma V^2 \quad . \quad (2.1)$$

Theoretical calculations (Brinkman et al, 1969) have explained the offset of the parabola from zero bias as being due to the barrier asymmetry arising from different work functions of the metal electrodes. Offsets larger than 50 meV were attributed to the distortion of the barrier potential due to impurities trapped in the junction. The parabolic fit by eq. (2.1) is considered to be approximate in the sense that it helps to determine the background conductance level for any additional structure which may appear superimposed on the tunnel characteristics. Fig. 2.1 illustrates such a case (Chen, Adler, 1970). The set of



Fig. 2.1

Normalized conductance curves for junctions with various electrodes. The curves are displaced vertically by 0.1 for clarity. The scales for Al-Al, Al-Mg junctions should be multiplied by two. The insert shows the sizes of zero bias anomalies of some junctions.





curves for different junctions is roughly parabolic with weak conductance increases at 118 meV due to inelastic excitation of aluminum hydrate (Geiger et al, 1969).

The insert in fig. 2.1 shows a structure around zero bias (commonly called the zero bias anomaly), the detection of which requires conductance measurements with a resolution to one part in 10^4 . Disregarding the relatively large conductance dip for the Al/Ni junction, which is associated with the magnetic properties of the nickel electrode (Rowell, 1969), small conductance decreases ($<1\%$) around zero bias in normal metal-insulator-junctions (seen here in Al/Al and Al/Ag junctions) were for a long time unexplained. The structure does not fall into any other previously investigated classes of zero bias anomalies explained on the basis of metallic inclusions (Giaver, Zeller, 1968) or magnetic impurities inside the insulating layer (Rowell, Shen, 1967).

A recent theory (Trofimenkoff et al, 1972) through a nonequilibrium treatment of the tunneling process has shown that the appearance of the low bias conductance minimum in M-I-M junctions is closely related to the finite electron relaxation rates in metal electrodes.

In what follows, we shall present the theoretical model of describing the non-equilibrium tunneling process with its predictions which are relevant to experimental verification.

2.2 Non-equilibrium theory of tunneling

A conventional theory of tunneling (Chapter 1) assumes that the tunneling electron is in thermal equilibrium with the rest of the electrons inside the metal. This is expressed by using the equilibrium Fermi-Dirac distribution function, f^0 , in the calculation of the tunneling current.

Consider, however, the following argument. An electron which penetrates the barrier finds itself at certain energy level in the host metal. At He⁴ temperatures, the final state of the electron is such that even at small imposed biases ~ 1 meV, it is energetically well above the thermally smeared Fermi sea ($1 \text{ K} = 86 \text{ } \mu\text{V}$). The existing non-equilibrium situation is neutralized only after a short period of time which is characterized by the relaxation processes in the metal. During the time the excited state is occupied, by the virtue of Pauli exclusion principle, all incoming electrons are effectively blocked from entering the same state. If the decay times of the excitation were of the same order of magnitude as the time an electron decides

to penetrate the barrier, the blocking of the available states would manifest itself by a strong decrease in the conductance of the tunnel junction. The use of equilibrium Fermi-Dirac distribution function is then equivalent to an assumption that the thermalization is immediate. In other words, the relaxation times of the interactions are assumed to be equal to zero.

To obtain quantitative predictions of the above mentioned process, a non-equilibrium distribution function has to be found, characteristic of the existing situation in the metal electrode. This is done by solving a transport model for the tunnel current, based upon the Boltzmann equation.

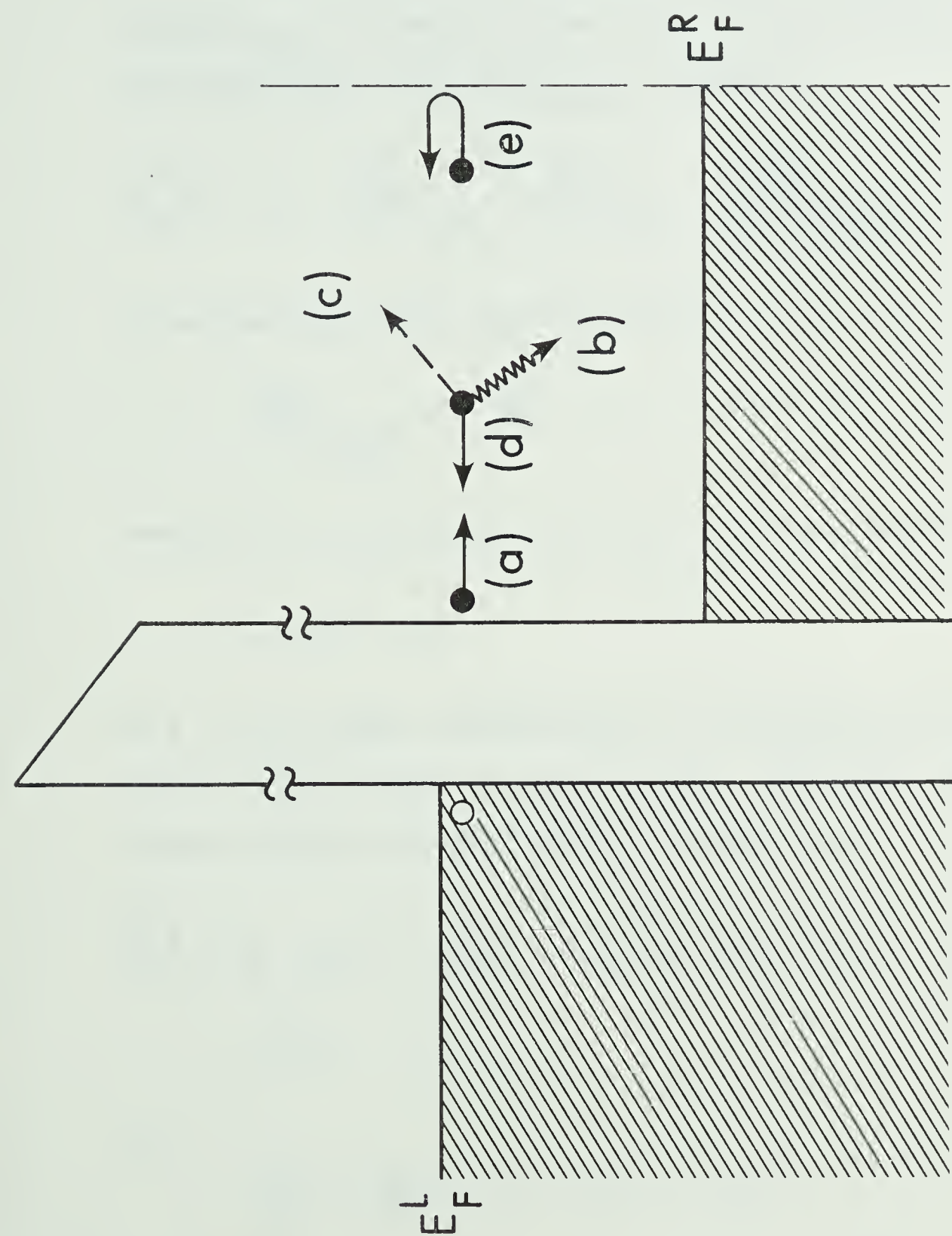
2.3 Description of the model

With reference to fig. 2.2, assume that an electron tunnels from a state ψ_1 into a state ψ_2 . By the virtue of Pauli exclusion principle the final state ψ_2 is unavailable for tunneling as long as it is occupied. However, through various scattering processes, the electron is scattered out of the occupied state. The competing mechanisms of filling and emptying the states soon establish across the junction a steady state in which the rate of change of the distribution function with time is zero, $\partial f / \partial t = 0$.

Fig. 2.2

Schematic diagram of scattering processes:

- a) electron in a forward direction
- b) inelastic scattering by phonon emission
or absorption
- c), d) elastic impurity scattering
- e) specular boundary scattering



Balancing the rate of change of the distribution function in metal 2 due to incoming $(\partial f_2/\partial t)_{1 \rightarrow 2}$ and outgoing $(\partial f_2/\partial t)_{2 \rightarrow 1}$ electron flux with losses due to scattering processes, $(\partial f_2/\partial t)_{\text{scatt}}$ we have:

$$\left(\frac{\partial f_2}{\partial t}\right) = 0 = \left(\frac{\partial f_2}{\partial t}\right)_{1 \rightarrow 2} + \left(\frac{\partial f_2}{\partial t}\right)_{2 \rightarrow 1} + \left(\frac{\partial f_2}{\partial t}\right)_{\text{scatt}} . \quad (2.2)$$

In relaxation time approximation

$$\left(\frac{\partial f}{\partial t}\right)_{\text{scatt}} = - \frac{\Delta f}{\tau} \quad (2.3)$$

where Δf is the deviation of f from equilibrium

$$f = f^0 + \Delta f \quad (2.4)$$

and τ is a time characteristic of scattering processes which bring f back to equilibrium. With the help of Fermi golden rule, eq. (2.2) is written as

$$\begin{aligned} \frac{\partial f_2}{\partial t} &= \frac{2\pi}{\hbar} |M_{12}|^2 \rho_1 f_1 (1 - f_2) - \frac{2\pi}{\hbar} |M_{12}|^2 \rho_1 f_2 (1 - f_1) \\ &\quad - \frac{\Delta f_2}{\tau_2} \end{aligned} \quad (2.5)$$

or

$$\frac{\Delta f_2}{\tau_2} = \frac{2\pi}{\hbar} |M_{12}|^2 \rho_1 (f_1 - f_2) . \quad (2.6)$$

By symmetry a similar equation is written for f_1

$$\frac{\Delta f_1}{\tau_1} = \frac{2\pi}{\hbar} |M_{12}|^2 \rho_2 (f_2 - f_1) . \quad (2.7)$$

Since the relevant quantity which enters the calculation of the tunneling current is the difference in the distribution functions (eq. 1.8), the two equations above are solved in that form:

$$f_1 - f_2 = \frac{f_1^0 - f_2^0}{1 + \frac{2\pi}{h} |M_{12}|^2 [\rho_1 \tau_2 + \rho_2 \tau_1]} . \quad (2.8)$$

On the basis of experimental evidence, we expect that the deviations from equilibrium are small. This permits to rewrite eq. (2.8)

$$f_1 - f_2 = (f_1^0 - f_2^0) \left(1 - \frac{2\pi}{h} |M_{12}|^2 [\rho_1 \tau_2 + \rho_2 \tau_1] \right) . \quad (2.9)$$

Therefore instead of the usual difference in the equilibrium distribution functions $(f_1^0 - f_2^0)$, (eq. (1.8)), the above relationship between f_1 and f_2 should be used in the calculation of the tunneling current. In the next section we shall consider the nature of the scattering processes, in order to determine the different relaxation mechanisms present in the metal.

2.4 Scattering mechanism

An electron in the metal undergoes a number of collisions which in general may alter its energy and momentum. Inelastic scattering due to phonon emission and absorption is characterized by a temperature and energy dependent relaxation time $\tau(\epsilon, T)$. A first order calculation applied to an interacting electron-phonon gas (Wilkins, 1968) gives the following result:

$$\frac{1}{\tau_{ep}(\epsilon, T)} = \frac{2\pi}{\hbar} \int_0^\infty d(\hbar\omega) \alpha^2(\hbar\omega) F(\hbar\omega) [2N^0(\hbar\omega) + 1 + f^0(\epsilon + \hbar\omega) - f^0(\epsilon - \hbar\omega)] \quad (2.10)$$

where ϵ is the excitation energy measured relative to the Fermi level. $\alpha^2 F$ is a product function involving the electron-phonon coupling function $\alpha^2(\hbar\omega)$ and the phonon density of states $F(\hbar\omega)$. The equilibrium distribution function for the phonons is given by

$$N^0 = \frac{1}{e^{\frac{\hbar\omega}{k_B T}} - 1} \quad . \quad (2.11)$$

Since the evaporated films are polycrystalline and thus have a characteristic of an isotropic material, the relaxation time τ_{ep} is assumed to be isotropic.

To facilitate a comparison of the theory with the experiment it is necessary to investigate the

behaviour of τ_{ep} at low temperatures and low excitation energies. Approximating $\alpha^2 F$ at low frequencies by a power law behaviour

$$\alpha^2 F = a_n \omega^n \quad n = \text{integer}$$

$$a_n = \text{constant}$$

Wattamaniuk (Wattamaniuk, 1972) found that

$$\frac{1}{\tau_{ep}(\epsilon)} = \frac{\pi a_1}{\hbar} [\epsilon^2 + (\pi k_B T)^2] \quad (2.12)$$

for $n = 1$, whereas for $n = 2$

$$\frac{1}{\tau_{ep}(\epsilon)} \xrightarrow{\epsilon \rightarrow 0} \frac{2\pi a_2}{\hbar} 7\zeta(3) (k_B T)^3 \quad (2.13)$$

$$\frac{1}{\tau_{ep}(\epsilon)} \xrightarrow{T \rightarrow 0} \frac{2\pi a_2}{\hbar} \frac{|\epsilon|^3}{3} \quad (2.14)$$

where $\xi(x)$ is a Riemann zeta function.

The two limiting cases of τ_{ep} appear as a result of a controversy which at the present time exists on the low energy limit of $\alpha^2 F$. At low frequencies $F(\omega)$ in the Debye approximation varies as ω^2 . Therefore for $n = 2$, $\alpha^2(\hbar\omega)$ is a constant. Experimental results (Goy, Castaing, 1973) point to this behaviour. Theoretical calculations (Carbotte, Dynes, 1968; Allen, Cohen, 1970) indicate a possible linear behaviour of $\alpha^2 F$ due to Umklapp processes. We shall consider both

cases separately, hoping that the experimental results will favour one limit.

Lacking detailed knowledge about the structure of evaporated films, scatterings due to lattice defects, impurities and diffuse boundaries are characterized by a constant relaxation time τ_i i.e. the scattering is considered to be energy and temperature dependent.

Another mechanism by which the blocking of the incoming electron flow is decreased, is obtained by an application of a magnetic field perpendicular to the direction of the tunnel current.

An electron which penetrates the barrier will travel away from it and can propagate across the film before being scattered. Assuming specular reflection at the boundary, the electron is reflected back with a reversed momentum. Upon reaching the metal-insulator interface, it may again be reflected specularly, thus reversing the momentum back to the original one. If the travel time over the length of the film is much less than the time an electron decides to penetrate the barrier or the scattering time, then the electron effectively remains in its quantum state and contributes to the blocking. For typical metals at energies close to the Fermi level $v_f \sim 10^8$ cm/sec and for a 1000 Å film, the travelling time back and forth is $\sim 2 \times 10^{-13}$ sec

which is at least two orders of magnitude less than the relaxation times due to electron-phonon interaction ($\sim 10^{-11}$ sec at He^4 temperatures).

In the presence of the magnetic field (Fig. 2.3), oriented perpendicularly to the direction of the tunnel current flow, the Lorentz force induced drift provides a mechanism, whereby the specularly reflected electrons move down the electrode and ultimately move away from the tunneling area. In a classical picture, the relaxation time associated with this process is then equated to the time it takes an electron to drift out of the junction area and thus be removed from the forward blocking direction. It is assumed that at low biases the magnetic field introduces no appreciable changes in the Fermi surface of the metal which could affect the tunnel current. The validity of this assumption is confirmed by the experimental results.

With reference to Fig. 2.3, $\overline{AA}$ represents the metal-insulator interface, which is at distance L away from the other end of the film. A magnetic field of B kG produces a circular motion with radius

$$R = \frac{mcV_f}{e} , \quad (2.15)$$

where c is speed of a light, and V_f is the velocity of the electron at the Fermi level. During the time



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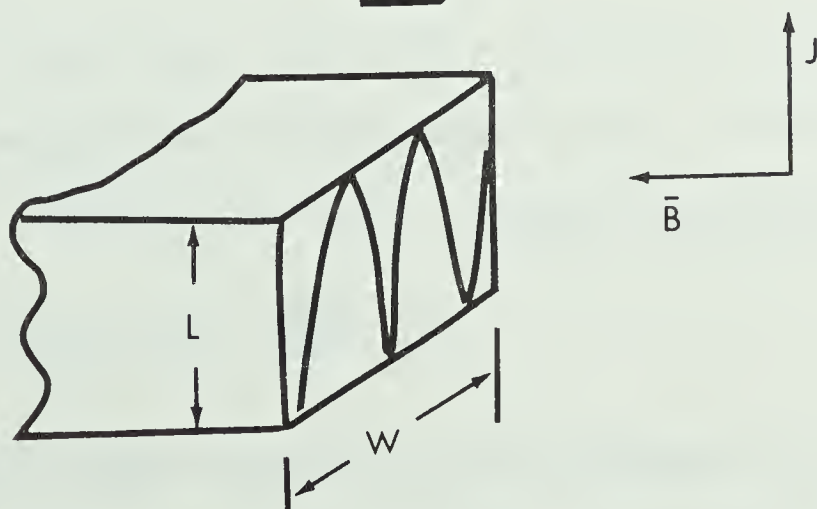
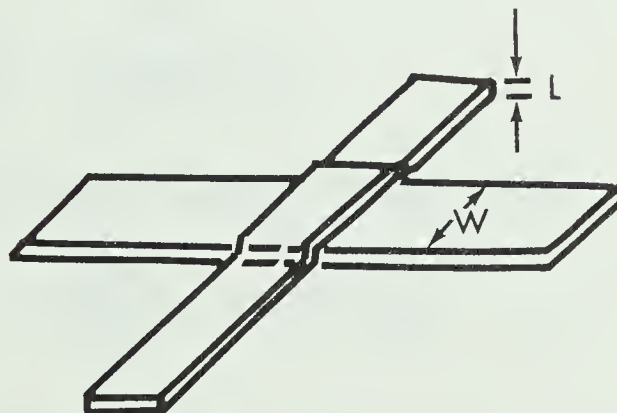
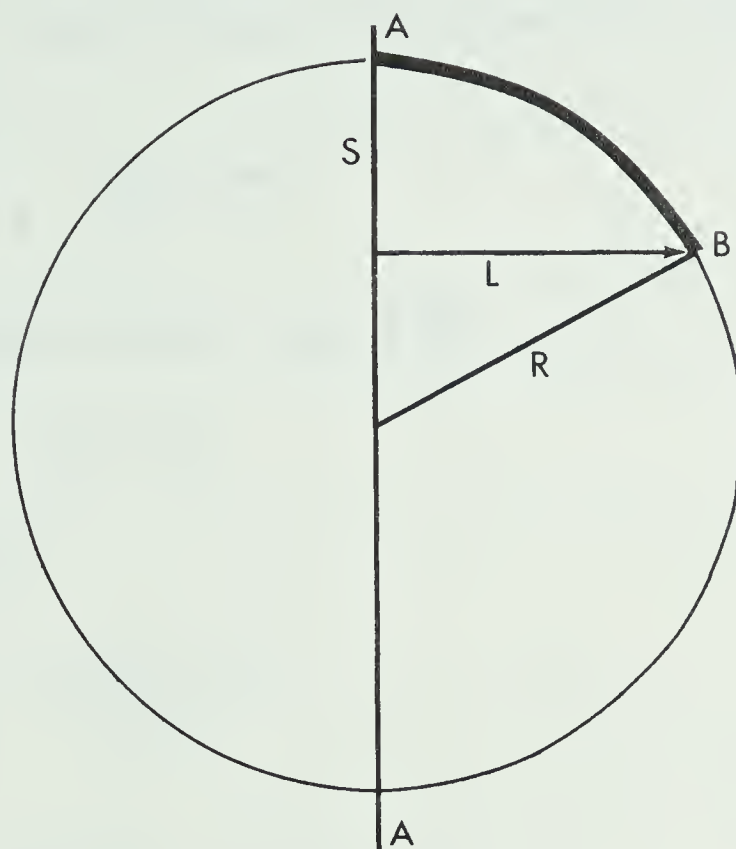
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Fig. 2.3

Schematic illustration of magnetic field induced drift velocity of a tunneling electron.



$\tau_{AB} = \frac{\overline{AA}}{V_f}$, the electron drifts down the electrode a distance S

$$S = R - \sqrt{R^2 - L^2} \quad (2.16)$$

Approximating $\overline{AB}$ by a chord $\overline{AB}$

$$\overline{AA} = \sqrt{S^2 + L^2} \quad (2.17)$$

τ_{AB} becomes:

$$\tau_{\overline{AA}} = \frac{\sqrt{S^2 + L^2}}{V_f} \quad (2.18)$$

The drift velocity is given as:

$$V_{\text{drift}} = \frac{S}{\tau_{\overline{AA}}} = \frac{SV_f}{\sqrt{S^2 + L^2}} \quad (2.19)$$

and thus if w denotes the width of the film;

$$\tau_{\text{drift}} = \left(\frac{V_{\text{drift}}}{w} \right)^{-1} = \frac{w\sqrt{2}}{V_f} \left(1 - \sqrt{1 - \frac{L^2}{R^2}} \right)^{-1/2} \quad (2.20)$$

For $L = 1000 \text{ \AA}$ and $R(60 \text{ kG}) = 20000 \text{ \AA}$, $L/R \ll 1$ and we can expand the square root in eq. (2.20) in powers of L/R . Keeping the first non-zero term we have:

$$\tau_{\text{drift}}^{(B)} = \frac{2mc}{eB} \left(\frac{w}{L} \right) \quad (2.21)$$

The final result shows that the effect of a magnetic field is to reduce the blocking by a rate which depends entirely on the geometry of the junction via the $(\frac{w}{L})$ ratio.

A magnetic field applied parallel to the tunnel current provides no Lorentz force on the electron and thus should have no effect on the size of the zero bias anomaly.

Recapitulating, we have considered three possible mechanisms which may scatter electrons from a given state:

- a) Energy and temperature dependent electron-phonon scattering time.
- b) Temperature and energy independent impurity scattering time, which includes contributions from lattice defects and diffuse boundaries.
- c) Scattering due to magnetic field induced drift velocity of the tunneling electron.

Since the probability of a scattering is inversely proportional to the relaxation time and since the different scattering mechanisms are independent of each other, we can write

$$\frac{1}{\tau} = \frac{1}{\tau_{ep}} + \frac{1}{\tau_i} + \frac{1}{\tau_{drift}} , \quad (2.22)$$

where τ is the effective relaxation time of an excited electron.

2.5 Predictions of the theory

Substituting eq. (2.9) into eq. (1.8) the total tunneling current I is given as

$$I = I_0 + \delta I, \quad (2.23)$$

where I_0 is the equilibrium current and δI is the blocking current

$$\delta I = \frac{4\pi meA}{h^3} \int_0^\infty (f^0(E) - f^0(E + eV)) dE \int_0^{E_x} D^2(E_x) \cdot \left(\frac{1}{2\pi h} \frac{\tau_1 (E - E_{f1})}{\rho_1(E_x)} + \frac{\tau_2 (E - E_{f1} + eV)}{2\pi h \rho_2(E_x + eV)} \right). \quad (2.24)$$

When writing the above equation we assume that the energy dependence of the relaxation time is coming only from the energy dependence of the electron-phonon counterpart.

Notice the dependence of δI in the square of the barrier transmission coefficient, thus making δI a sensitive function of the insulator thickness. Furthermore the density of states factors did not cancel out as it happened in the calculation of the equilibrium tunneling current I_0 . A density of states, rapidly varying with energy, could then produce a structure in δI . However, for small applied bias, where experimentally the blocking current is observed, the density of states is a smooth function of energy,

the variation of which would not be expected to have significant effect on δI . In fact, we can replace the ratio $\frac{1}{2\pi\hbar} \frac{D}{\rho_i}$, $i = 1, 2$, by its value at the Fermi level providing $eV \ll E_{fi}$, $i = 1, 2$

$$\frac{D}{2\pi\hbar\rho_i} = \frac{D(E_{fi})}{2L_i} V_{fi} = \frac{1}{\tau_{Bi}}, \quad i=1,2 \quad (2.25)$$

where V_{fi} is the Fermi velocity and L_i is the thickness of the metal i . τ_B is the tunneling lifetime of an electron in i^{th} electrode.

Referencing the energies to the Fermi level of the left hand metal, and realizing that due to the difference in the Fermi functions the only significant contribution to δI arises from energies close to the Fermi level, we rewrite eq. (2.24) as

$$\delta I = - \frac{\sigma_0}{e} \int_{-\infty}^{+\infty} \left(F^0(\epsilon) - F^0(\epsilon + eV) \cdot \left(\frac{\tau_1(\epsilon)}{\tau_{B1}} + \frac{\tau_2(\epsilon + eV)}{\tau_{B2}} \right) \right) d\epsilon \quad (2.26)$$

where

$$F^0(\epsilon) = \frac{1}{e^{\epsilon/k_B T} + 1}$$

and σ_0 is the ideal zero bias conductance as defined in eq. (1.10)

$$\sigma_0 = \frac{4\pi me^2 A}{h^3} \int_0^{E_{f1}} D(E_x) dE_x \quad (2.27)$$

Eq. (2.26) can be further simplified realizing that τ , the effective relaxation time is an even function of the excitation energy since τ_{ep} by definition (eq. 2.10) is even. Using

$$F^O(\epsilon) - F^O(\epsilon + eV) = -F^O(-\epsilon - eV) - F^O(-\epsilon) \quad (2.28)$$

we rewrite eq. (2.26) as:

$$\delta I = - \frac{\sigma_o}{e} \int_{-\infty}^{\infty} \left(F^O(\epsilon) - F^O(\epsilon + eV) \right) \cdot \left(\frac{\tau_1(\epsilon)}{\tau_{B1}} + \frac{\tau_2(\epsilon)}{\tau_{B2}} \right) d\epsilon \quad (2.29)$$

The blocking conductance $\delta\sigma(V) = \delta I(V)/dV$, normalized to zero bias is given as:

$$\frac{\delta\sigma(V)}{\sigma_o} = - \int_{-\infty}^{\infty} d\epsilon \left(- \frac{\partial F^O(\epsilon)}{\partial \epsilon} \right) \cdot \left(\frac{\tau_1(\epsilon + eV)}{\tau_{B1}} + \frac{\tau_2(\epsilon + eV)}{\tau_{B2}} \right). \quad (2.30)$$

It may be easily verified that $\delta\sigma(V)$ is an even function of the applied bias V . Therefore, it is symmetric around zero bias.

In further discussions we assume that the junction is symmetric and that the applied magnetic field is equal to 0 kG. We write then

$$\tau_B = \tau_{B1} = \tau_{B2} \quad \text{and} \quad \tau_1(\epsilon) = \tau_2(\epsilon) = \tau(\epsilon) .$$

At 0 K we can evaluate the blocking conductance in a closed form,

$$\frac{\delta\sigma(V)}{\sigma_0} = - \frac{2\tau(eV)}{\tau_B} \quad (2.31)$$

where

$$\frac{1}{\tau} = \frac{1}{\tau_i} + \frac{1}{\tau_{ep}(eV, T=0)} \quad (2.32)$$

Recalling eqs. (2.12)-(2.14), we write

$$\frac{\delta\sigma(V)}{\sigma_0} = - \frac{2/\tau_B}{\frac{1}{\tau_i} + \left(\frac{\pi a_1}{\hbar}\right)(eV)^2} \quad (2.33)$$

for $\alpha^2_F = a_n \omega^n$, $n = 1$, and

$$\frac{\delta\sigma(V)}{\sigma_0} = - \frac{2/\tau_B}{\frac{1}{\tau_i} + \left(\frac{2\pi a_2}{3\hbar}\right)|eV|^3} \quad (2.34)$$

for $n = 2$. Figs. 2.4 and 2.5 illustrate the blocking conductance and its derivative $d\delta\sigma(V)/dV$ for $n = 1$ and $n = 2$. For finite temperatures the integral in eq. (2.30) has to be calculated numerically. We write eq. (2.30) then as

$$\frac{\delta\sigma(V)}{\sigma_0} = - \int_{-\infty}^{\infty} \frac{dx}{(e^x + 1)(e^{-x} + 1)} \left\{ \frac{\tau_1(xk_B T + eV)}{\tau_{B1}} + \frac{\tau_2(xk_B T + eV)}{\tau_{B2}} \right\} \quad (2.35)$$

The derivative of the blocking conductance $\frac{1}{\sigma_0} \frac{d\delta\sigma(V)}{dV}$ is given by



Fig. 2.4

Blocking conductance and its derivative at $T=0$ K
(assuming $\alpha^2 F = a_n \omega^n$, $n = 1$).

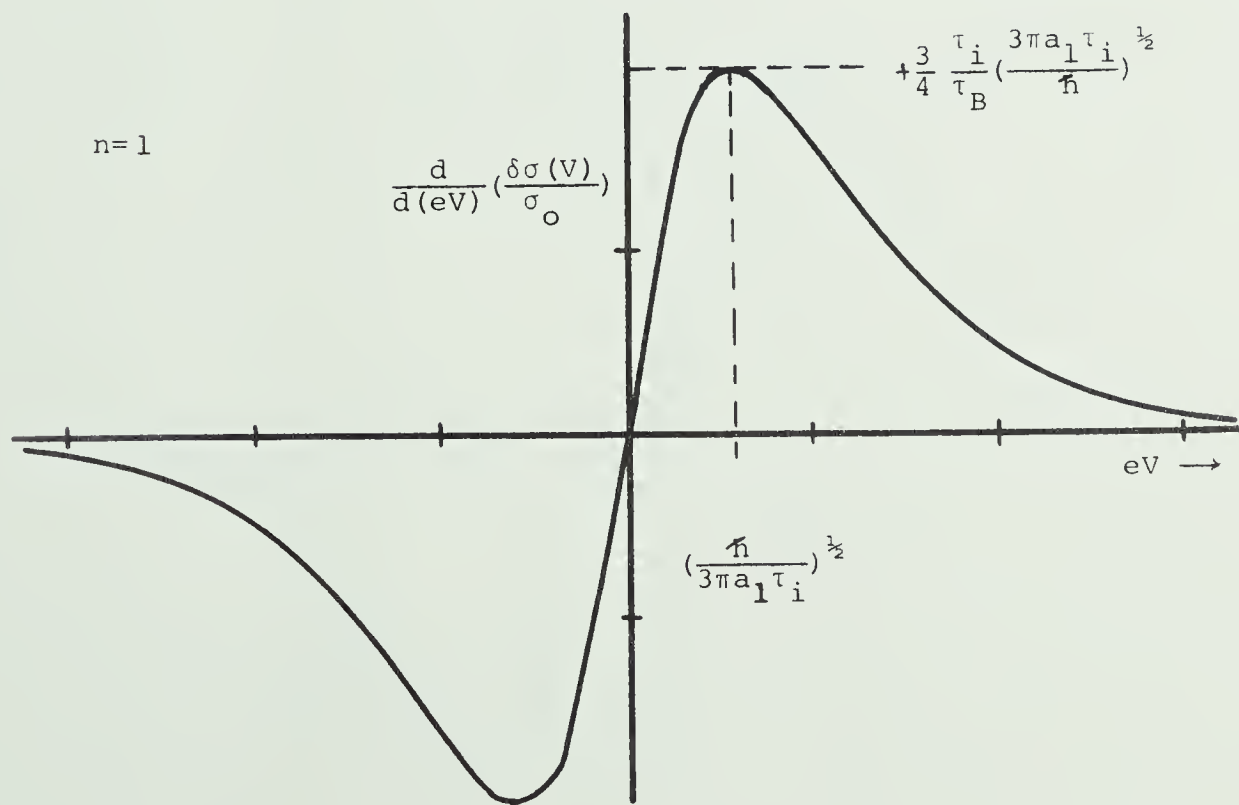
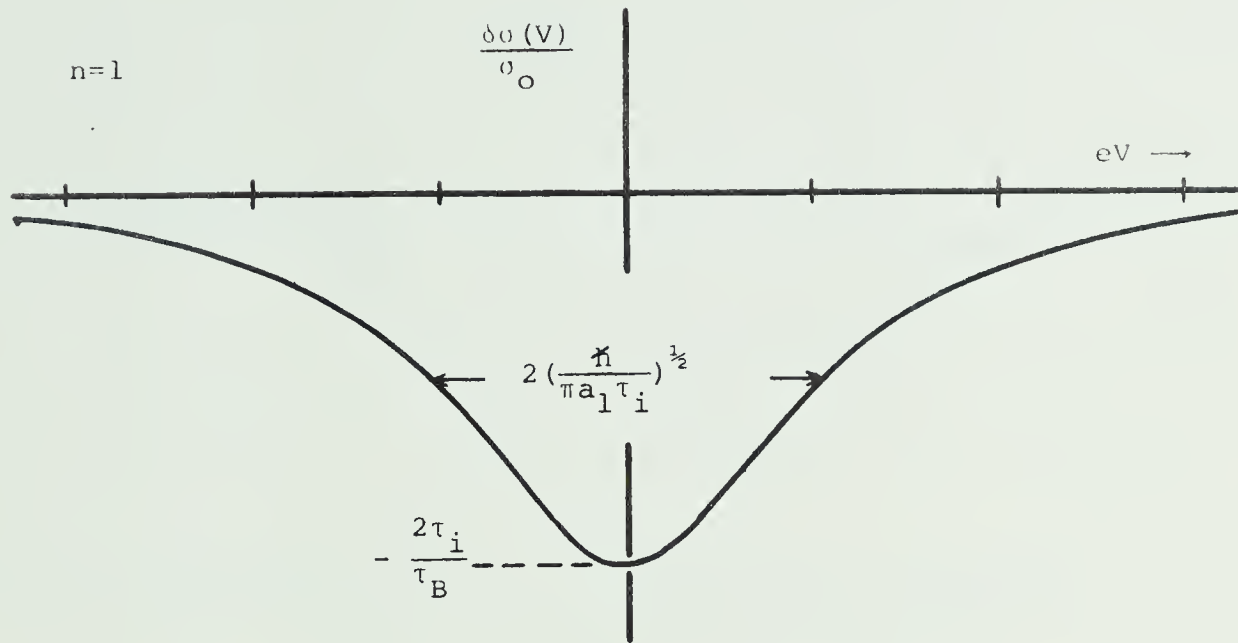
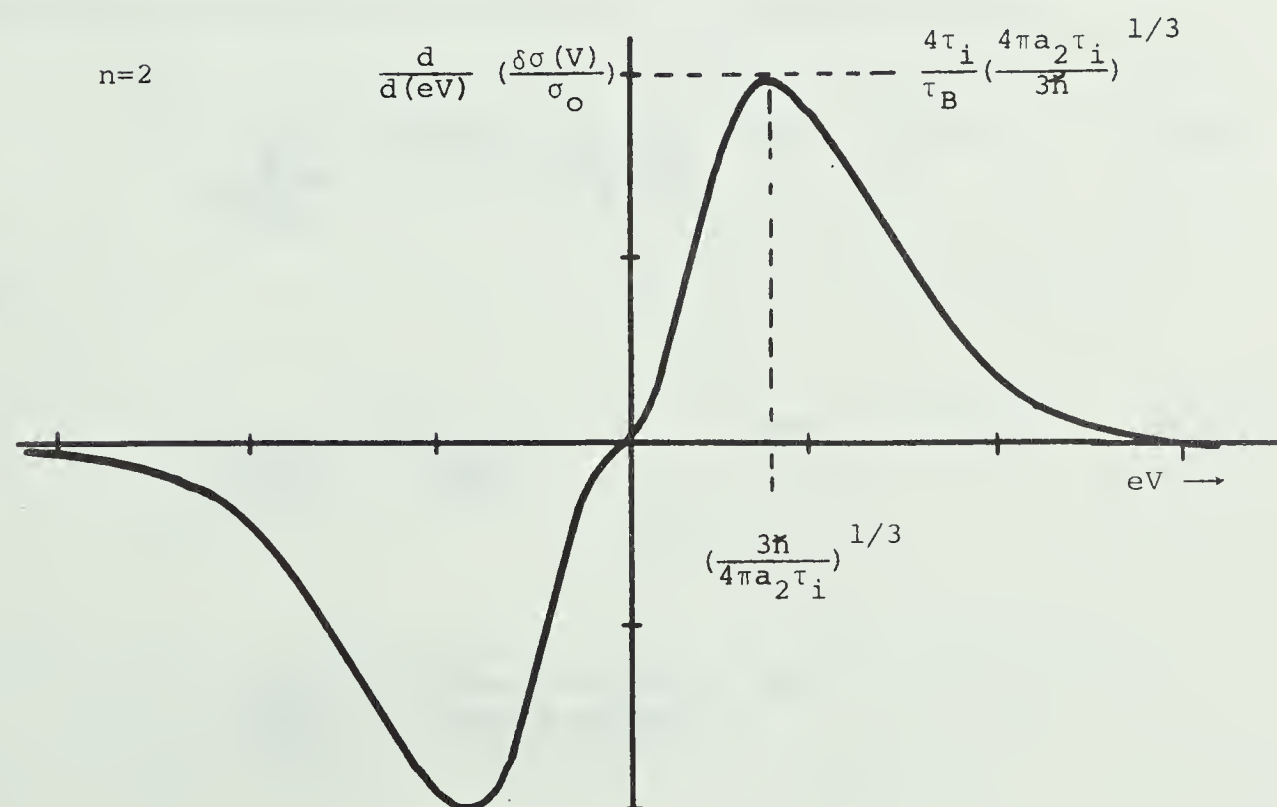
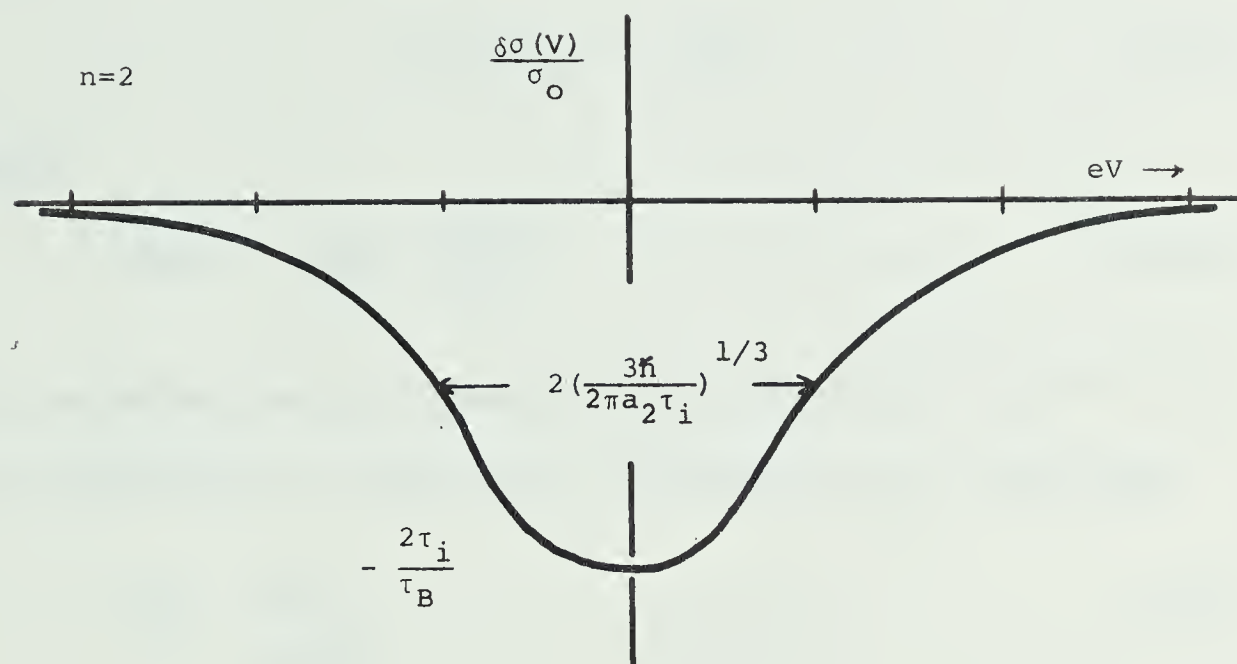




Fig. 2.5

Blocking conductance and its derivative at $T=0$ K
(assuming $\alpha^2_F = a_n \omega^n$, $n = 2$).



$$\frac{1}{\sigma_0} \frac{d\delta\sigma(V)}{dV} = \int_{-\infty}^{\infty} \frac{1}{(e^x+1)(e^{-x}+1)} [S_1(xk_B T + eV) + S_2(xk_B T + eV)] \quad (2.36)$$

where

$$S(\varepsilon) = - \frac{d}{dV} \left[\frac{\tau(\varepsilon)}{\tau_B} \right] \quad (2.37)$$

To parameterize the theoretical curves for $T \neq 0$ K, it is convenient to introduce a parameter Γ_n , given by:

$$\Gamma_n^j = \frac{\hbar}{\pi \tau_i a_n^j} \quad \begin{array}{l} j = 1, 2 \\ n = 1, 2 \end{array} \quad (2.38)$$

This follows directly from the limiting behaviour of the effective relaxation time at low temperatures.

$$\tau \sim \frac{\hbar}{\frac{\hbar}{\pi a_1 \tau_i} + \varepsilon^2 + (\pi k_B T)^2} \quad \text{for } \alpha^2_F \sim \omega \quad (2.39)$$

and

$$\tau \sim \frac{\hbar}{\frac{\hbar}{\pi a_2 \tau_i} + \frac{2|\varepsilon|^3}{3}} \quad \text{for } T \rightarrow 0 \quad (2.40)$$

$$\tau \sim \frac{\hbar}{\frac{\hbar}{\pi a_2 \tau_i} + 14\xi(3)(k_B T)^3} \quad \text{for } \varepsilon \rightarrow 0$$

$$\text{if } \alpha^2_F \sim \omega^2 \quad (2.41)$$

Figs. 2.6 and 2.7 illustrate the behaviour of the blocking conductance at zero bias for a symmetrical junction as a function of temperature. A more sensitive comparison of the theory with the experiment is obtained by examining the behaviour of the maxima (minima) in $\frac{1}{\sigma_0} \frac{d\delta\sigma}{dV}$ with temperature. Figs. 2.8 and 2.9 show that the maximum in $\frac{1}{\sigma_0} \frac{d\sigma}{dV}$ decreases in size as the temperature increases. The data calculations were normalized to 1 K. The corresponding peak positions shift to a higher bias.

The application of a magnetic field leads only to a renormalization of the scattering time associated with the impurities.

$$\frac{1}{\tau_i} \rightarrow \frac{1}{\tau_{i,\text{drift}}} = \frac{1}{\tau_i} \left(1 + \frac{\tau_i}{\tau_{\text{drift}}}\right) \quad (2.42)$$

This for example, at $T = 0$ K, and for $\alpha^2 F \sim \omega$, results in a shift of the position, V_{max} , of the maximum in $\frac{1}{\sigma_0} \frac{d\delta\sigma}{dV}$. Using eq. (2.33) we find

$$V_{\text{max}}(B) = V_{\text{max}}(0) \left(1 + \frac{\tau_i}{\tau_{\text{drift}}}\right)^{1/2} \quad (2.43)$$

There is a corresponding change in the peak height:

$$\frac{1}{\sigma_0} \frac{d\delta\sigma(V_{\text{max}}, B)}{dV} = \frac{1}{\sigma_0} \frac{d\delta\sigma(V_{\text{max}}, 0)}{dV} \left(1 + \frac{\tau_i}{\tau_{\text{drift}}}\right)^{-3/2} \quad (2.44)$$



Fig. 2.6

Temperature dependence of the blocking
conductance at zero bias ($\alpha^2 F = a_1 \omega$).

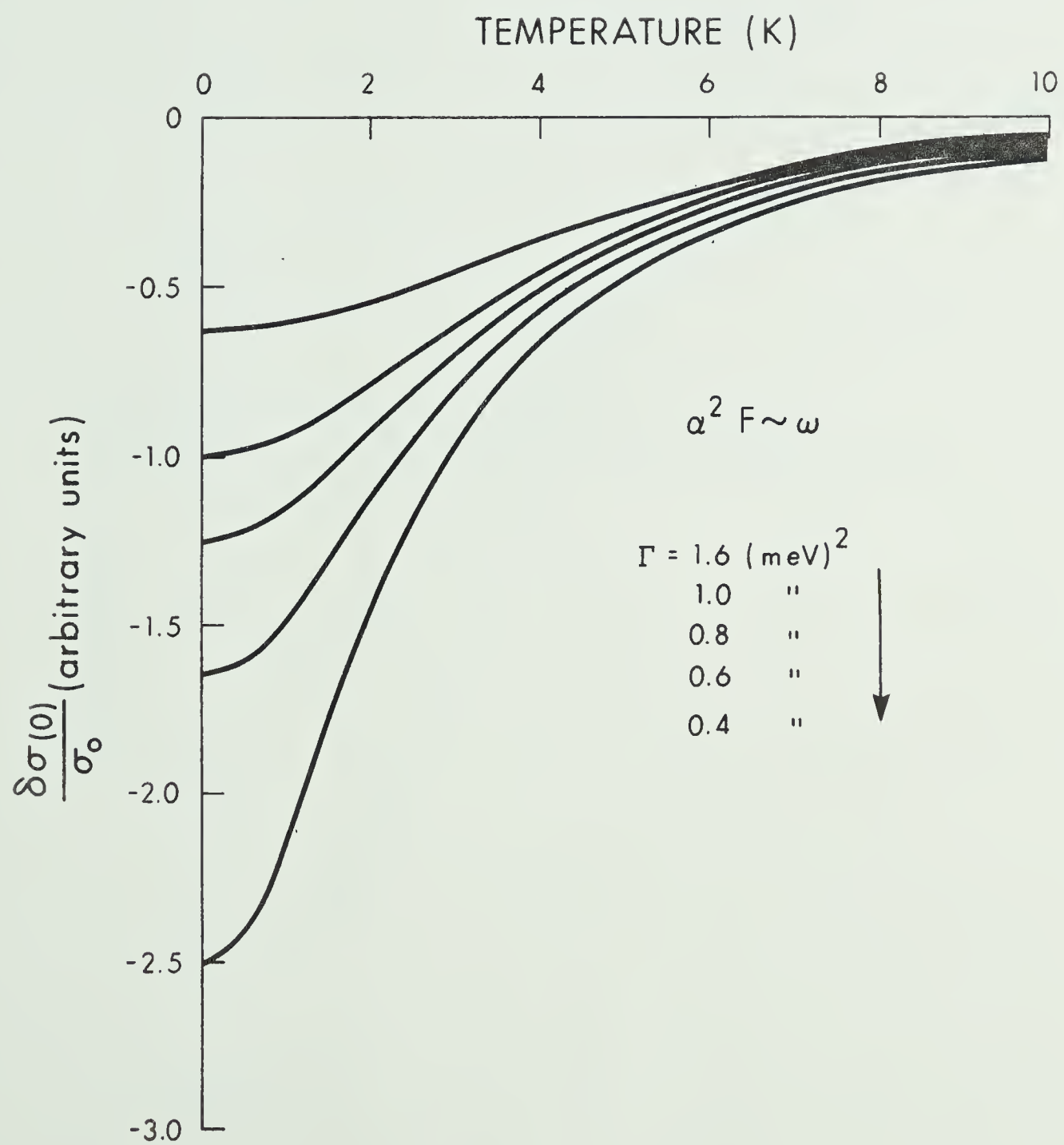
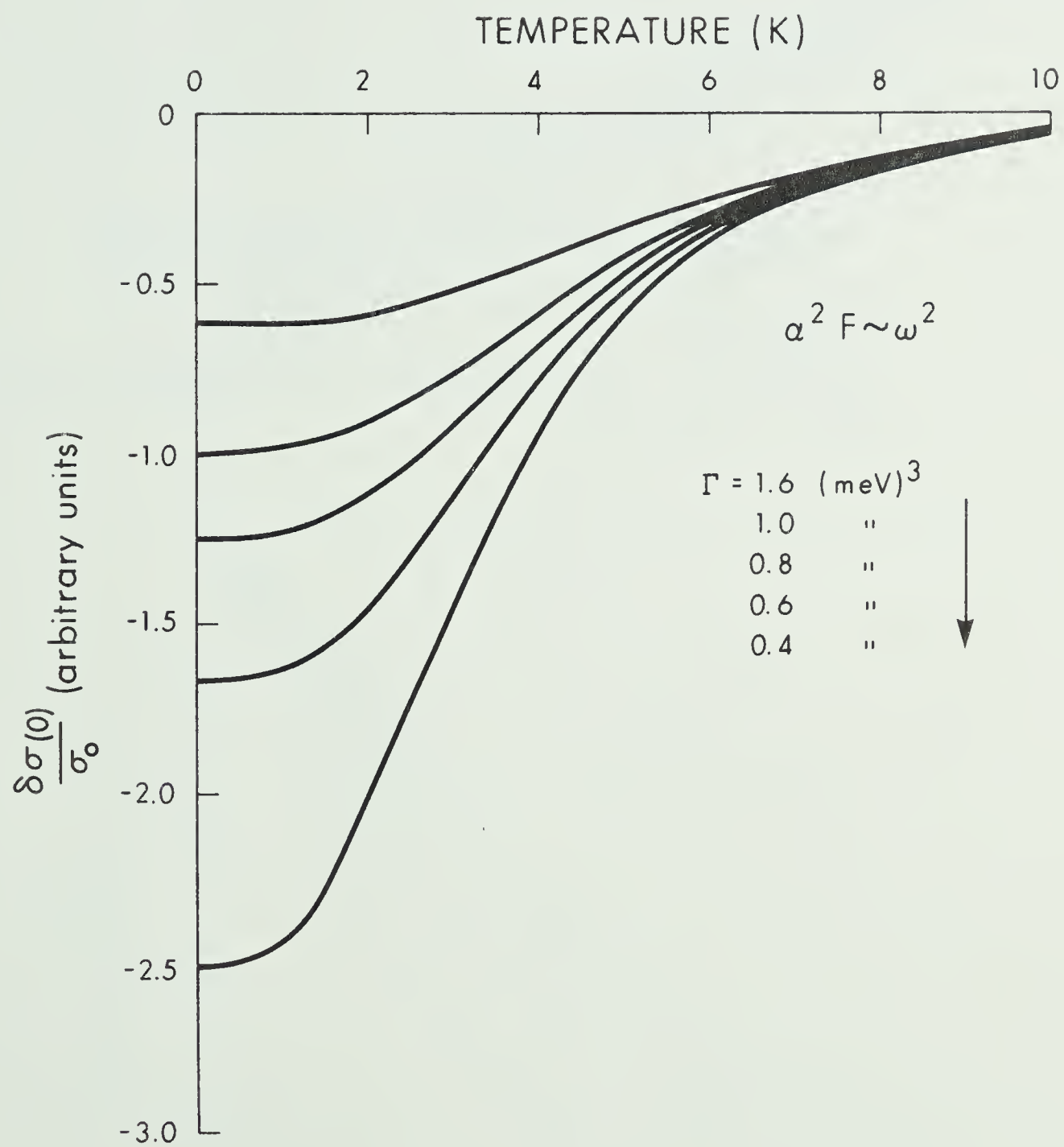


Fig. 2.7

Temperature dependence of the blocking
conductance at zero bias ($\alpha^2_F = a_2 \omega^2$).



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100. 100. 100.

Fig. 2.8

Temperature dependence of peak positions,
 $V_{\max}$ (upper diagram) and peak amplitudes
 $\frac{1}{\sigma_0} \frac{d\delta\sigma_e}{dV} \Big|_{V_{\max}}$ (lower diagram) for different values
of Γ ($\alpha_F^2 = a_1 \omega$).

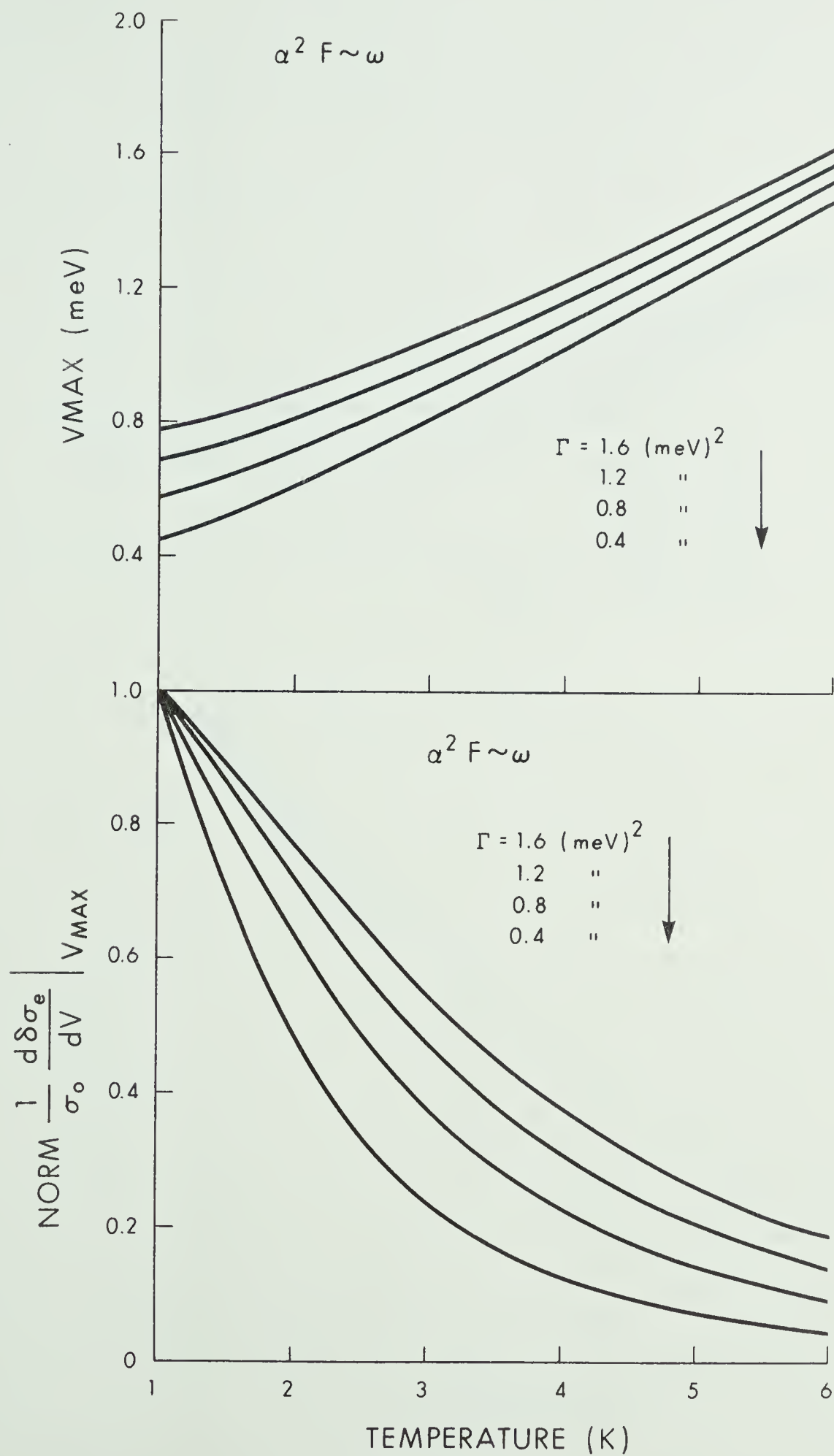


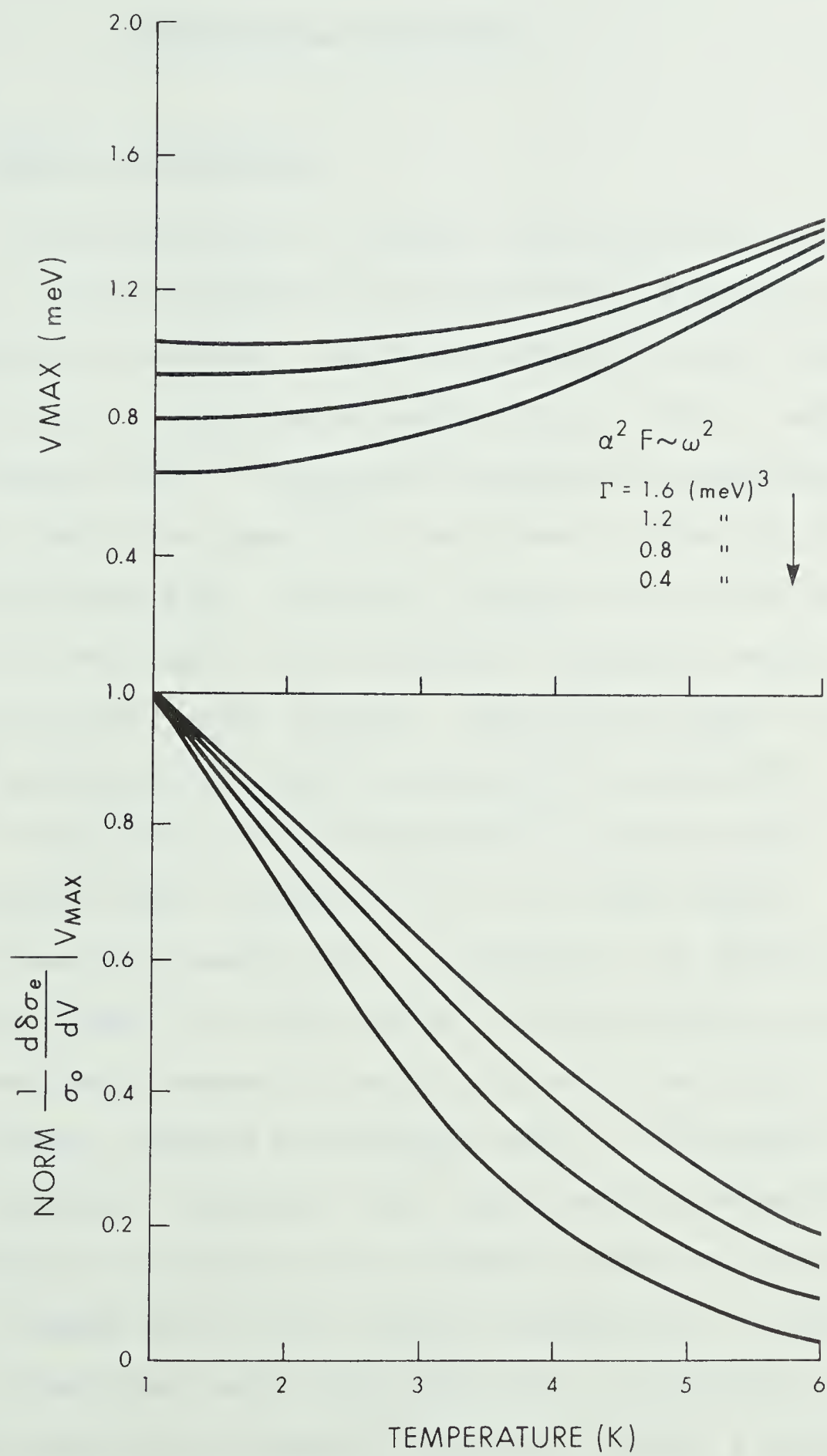


Fig. 2.9

Temperature dependence of peak positions,

$V_{\max}$ (upper diagram) and peak amplitudes

$\frac{1}{\sigma_0} \left. \frac{d\delta\sigma_e}{dV} \right|_{V_{\max}}$ (lower diagram) for different values
of Γ ($\alpha^2 F = a_2 \omega^2$).



CHAPTER 3

EXPERIMENTAL TECHNIQUES

3.1 Sample preparation

The preparation of tunnel junctions was carried out in a vacuum system by an evaporation of metals onto a suitable substrate. There are basically three steps involved in the process of preparation. First a metal film (base layer) of required thickness is deposited. A thin insulating layer is then formed on the top of the evaporated film. Finally a cross-strip of an another metal is evaporated, thus forming a composite metal-insulator-metal (MIM) system. Evaporated layers of In or Ag served as contacts for electrical connection.

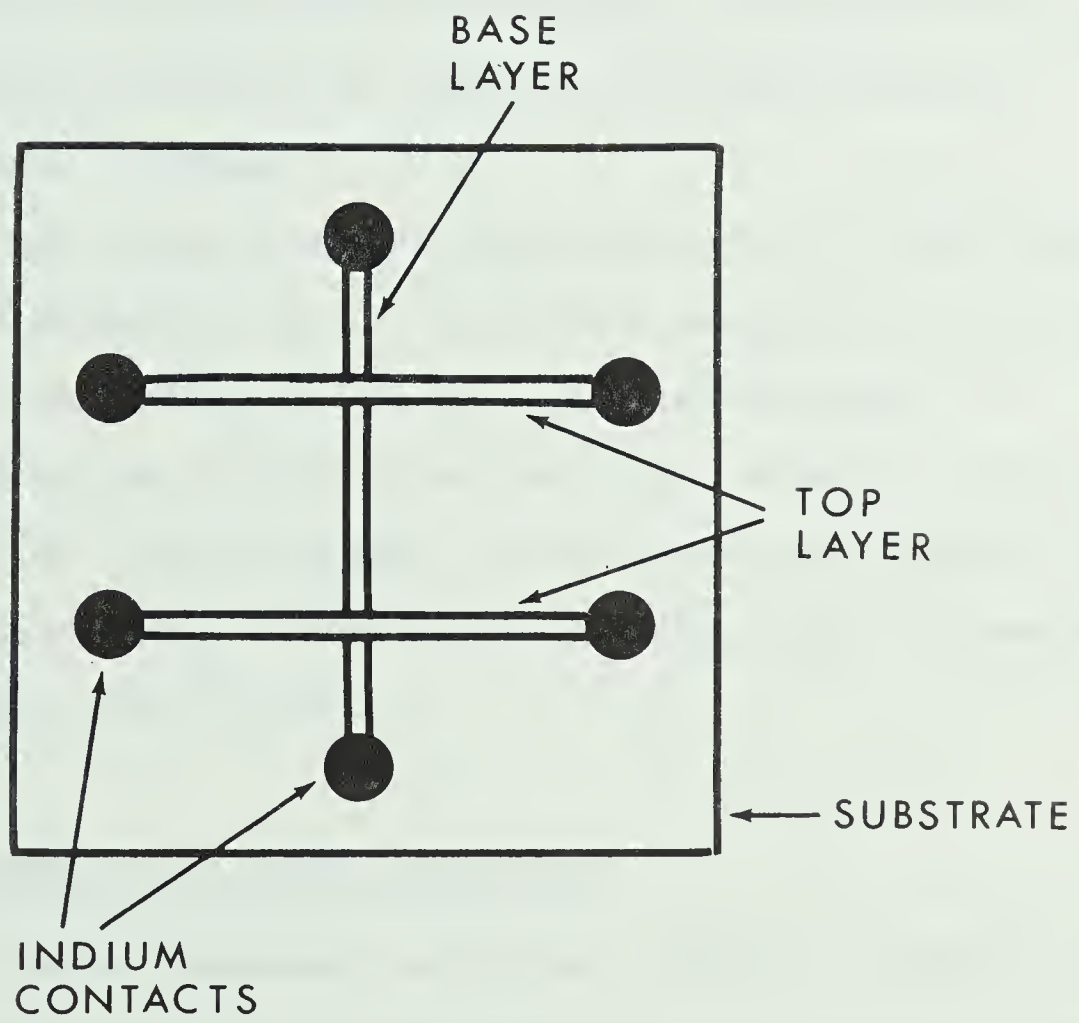
The junctions were prepared on Fisher brand microscopic glass slides cut to a 1/2 inch square. The slides were washed with a detergent, air dried and flame polished. For some Bi/Bi junctions freshly cleared mica was used, washed in methyl alcohol. The substrates were further cleaned by exposing them to the plasma of glow discharge (Holland, 1961) prior to film deposition. The size of the substrates allowed to make two junctions with a common base layer without breaking the vacuum.

The films were evaporated from a resistively heated nonvolatile support (filament) through a pattern



Fig. 3.1

Layout of the Sample



forming mask, in close vicinity of which the substrate was placed. The filaments were mounted on a rotating carousel which allowed a proper indexing of the evaporated material. Cylindrical quartz chimneys placed around them prevented a mutual cross-contamination of the metals. Table 3.1 lists the selection of filaments for evaporation. The distance between the vapour source and the substrate was 7 inches.

The vacuum chamber, enclosed in an 18 inch bell jar, was pumped by an oil diffusion pump with a liquid nitrogen cold trap backed by a mechanical pump. A zeolite trap was installed between the mechanical pump and the rest of the system. The system was ready for the evaporation after 1 hour of evacuation with a pressure lower than 2×10^{-6} torr.

3.2 Formation of tunnel barriers

A glow discharge technique (Miles and Smith, 1963) was used to prepare tunnel junctions of Mg and Al. It consists of setting up a discharge between two aluminum electrodes while the pressure of the system was maintained between 100-600 torr of either 99.5% pure oxygen or nitrogen of the same purity (for Mg only). The aluminum electrodes were 2 inches wide, separated 1/2 inch

Table 3.1

Selection of Materials for Evaporation

Metal	Purity	Supplier	Evaporation Source
Al	59	A.D. Mackay	F8-3X.030 W coil
Mg	59	Johnson Matthey	S17A-.005 Ta covered boat
Bi	69	Cominco	S39-.005 Ta S39-.005 Mo boat
Pb	69	Cominco	S39-.005 Mo boat
Au	59	Cominco	S39-.005 Mo S9A-.005 W boat

Evaporation sources supplied by R.D. Mathis Company

apart and placed 2 inch above the holder containing the glass slide with a freshly evaporated metal film. The polarity of the applied DC voltage was such that the evaporator which was conductively connected with one of the electrodes was at positive potential with respect to the second electrode. The thickness of a tunnel barrier grown by this method depended on the time the discharge was maintained, pressure in the system and the current flowing through the electrodes. For a successful preparation of a tunnel barrier it was important to keep a stable discharge without random fluctuations. Presumably the rapidly varying electric field produced pinholes in the thin insulator. The oxidation of Mg for 1-3 minutes in 100-200 torr of O_2 , with a glow discharge current of 5-15 mA was sufficient to produce tunnel junctions with resistances of nominally 200 Ω . Al required a longer oxidation time (5-10 minutes) and higher pressure (400 torr), while the current was 5-15 mA. To prepare junctions in nitrogen environment, the discharge had to be kept for 40-80 minutes with currents up to 40 mA and pressures ranging between 400-600 torr.

Repeated experiments of producing an oxide of Bi by the glow discharge technique ended in failure. However, a method of thermal oxidation (Hapase et al, 1967) yielded thick enough oxides to produce junctions

having resistances around 200 Ω . The oxidation procedure was as follows: After the deposition of the Bi film the vacuum was broken and the substrate was placed in an oven at 180°-220°C for 2 hours. Following this, the substrate was again placed in the substrate holder and the vacuum chamber re-evacuated for the evaporation of the cross-film.

3.3 Film thickness determination

The thickness of films during vacuum deposition was monitored by Sloan DTM-3 (Sloan Instr. Corp.) quartz crystal monitor. The measurement utilizes a principle that the resonance frequency of a piezoelectric crystal depends on the mass of the material deposited on the surfaces of the crystal (Eschbach and Kruidhoff, 1965). The monitor therefore consists of a crystal placed adjacent to a substrate onto which the film is deposited and the electrical equipment for measuring the change in its resonance frequency. Eq. (3.1) relates the thickness L of the deposited metal to the measured frequency shift Δf (Stockbridge, 1966)

$$L = C_1 C_2 \frac{\Delta f}{\rho} = \frac{C \Delta f}{\rho} \quad (3.1)$$

$$C = C_1 C_2$$

C_1 is a constant dependent on the thickness and cut of

the piezoelectric crystal, C_2 depends on the geometry of the distribution of the deposit over the crystal and ρ is the density of the material. The validity of eq. (3.1) is restricted to mass deposits which are at most 5% of the mass of the crystal itself (Steckelmacher, 1965). For all practical purposes this condition was satisfied. Since the density of thin films is different from that of the bulk due to voids in the film (Hartman, 1965) it is best to determine the mass sensitivity ratio C/ρ for each given material experimentally, combining the shift in the resonance frequency of the crystal with an optical thickness measurement using Tolansky interferometer (Tolansky, 1960).

The interferometer consists of two slightly inclined optical flats, one of them supporting the film which forms a step on the substrate. When the second optical flat is brought in contact with the film surface and the interferometer illuminated with a parallel monochromatic beam at normal incidence, dark fringes are observed which trace out the points of equal air-gap thickness. Their separation is $\lambda/2$ where λ is the wavelength of the monochromatic light. The fringes show a displacement as they pass over the film step edge. The displacement d expressed as a function of $\lambda/2$ fringe spacing gives the film thickness.

$$L = \frac{d}{\text{fringe spacing}} \frac{\lambda}{2} \quad (3.2)$$

In order that the phase change on reflection from the two sides of the step will be the same, it is necessary to coat the film as well as the exposed glass surface with the same reflecting silver layer.

Vrba (Vrba, 1971) has described these measurements in greater detail. The experimentally determined values of C/ρ are the following:

Al - 940 Å/Kc

Mg - 1480 Å/Kc

Bi - 268 Å/Kc

Pb - 235 Å/Kc

Au - 127 Å/Kc

The uncertainties in the mass sensitivity determination are approximately 5% and are of interferometric and geometric origin.

3.4 Temperature measurement and control

The temperatures were determined by a combination of vapour pressure and germanium resistance thermometer measurements. A 1958 scale of temperatures (Dijk et al, 1960) was used to convert the vapour pressure to temperature. Above the boiling of He^4 , a germanium thermometer (Scientific Instruments, # 10372) was used with a computer generated polynomial fit of the form

$$\frac{1}{T} = \sum_{k=0}^n a_k H_k (\ln R) \quad (3.3)$$

where a_k is the k^{th} expansion coefficient, H_k - the Chebyshev polynomial of order k , T - temperature, R - resistance of the thermometer.

By a controlled regulation of the He^4 vapour pressure, temperatures between 1 K and 4.2 K were obtained. Sommers (Sommers, 1954) described a convenient manostat which employs a thin teflon diaphragm, which bows out when there is a pressure difference across it, thus blocking the pumping orifice. The temperature fluctuations using this manostat did not exceed 5 mK around a preset value. A solid state temperature controller designed by Dr. Adler and Dr. Rogers was used to regulate temperatures above 4.2 K. The circuit is of the conventional Wheatstone bridge type, using a germanium thermometer as its sensing element and providing a proportional heater feedback to the regulated bath. It was capable of maintaining constant temperature within ± 1 mK at 5 K. The power dissipation in the thermometer was less than 10^{-8} W.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that proper record-keeping is essential for the integrity of the financial system and for the ability to detect and prevent fraud. The text also mentions the need for regular audits and the role of independent auditors in ensuring the reliability of the data.

2. The second part of the document focuses on the implementation of internal controls. It describes various measures that can be taken to minimize the risk of errors and misstatements, such as the separation of duties, the use of standardized procedures, and the establishment of a strong internal control environment. The document also highlights the importance of training and education for all personnel involved in the financial process.

3. The third part of the document discusses the role of technology in modern financial systems. It notes that the use of computerized systems can greatly improve the efficiency and accuracy of financial operations. However, it also points out that the use of technology introduces new risks, such as data security and system failures, which must be carefully managed.

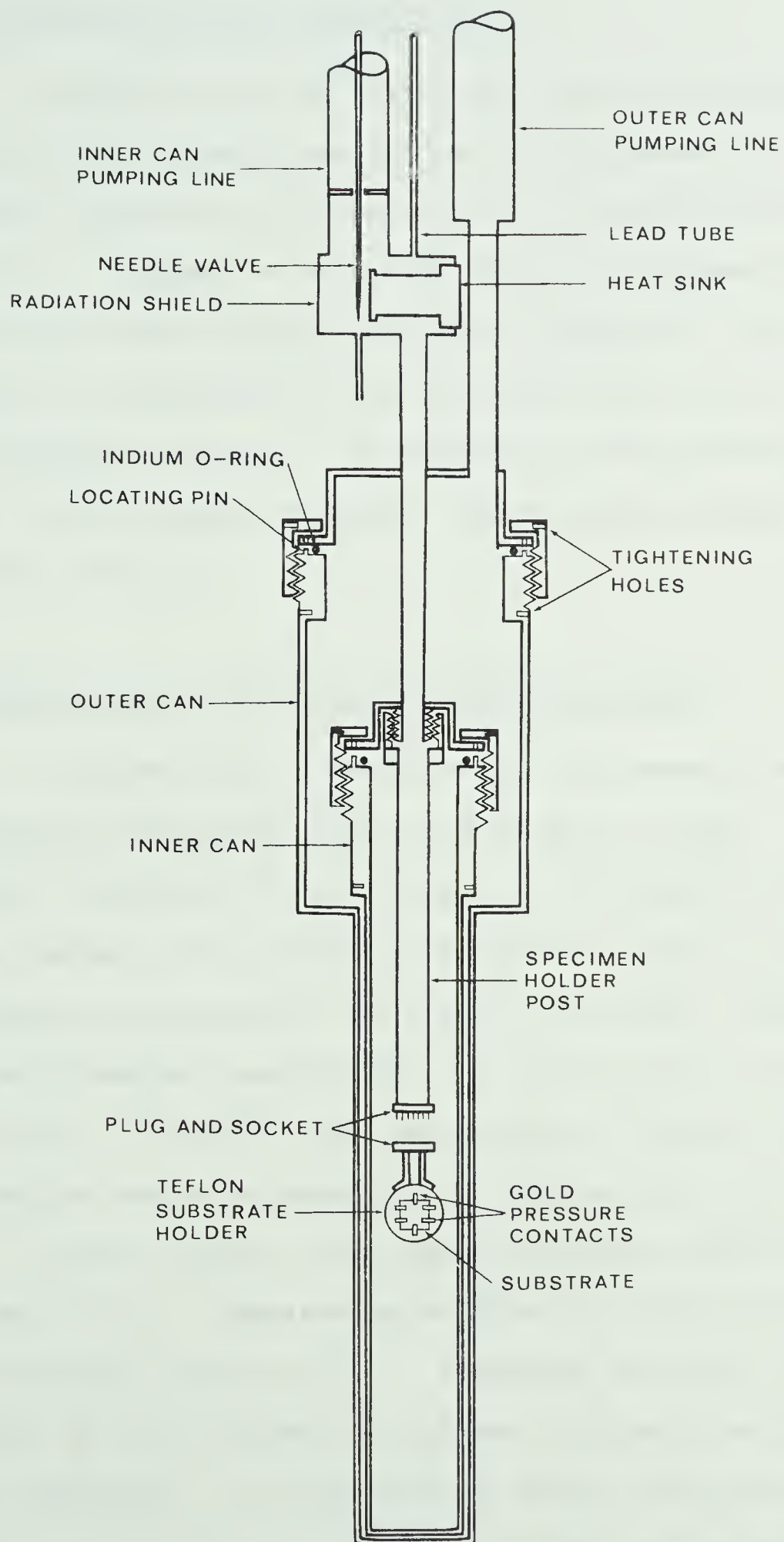
4. The fourth part of the document addresses the issue of transparency and accountability. It argues that financial institutions should be open and honest in their dealings with the public and should provide clear and accessible information about their operations. This includes the timely disclosure of financial statements and the establishment of a robust system for handling complaints and inquiries.

5. The fifth and final part of the document provides a summary of the key points discussed and offers some recommendations for further action. It stresses that the financial system is a complex and dynamic one, and that continuous improvement is necessary to ensure its long-term success. The document concludes by expressing confidence in the ability of the financial system to meet the challenges of the future.



Fig. 3.2

Schematic diagram of the cryostat



3.5 Production of low temperatures

A conventional He^4 cryostat facilitated measurements on tunnel junctions at low temperatures. A schematic diagram of the cryostat is illustrated on fig. 3.2. Indium O-rings with Apiezon N grease were used to seal the vacuum and sample chambers. The cryostat was designed to fit into the bore of a 70 kG superconducting magnet. By pumping on the helium liquid level, in the sample chamber, temperatures as low as 1 K were attained.

3.6 Measurement of tunneling characteristics

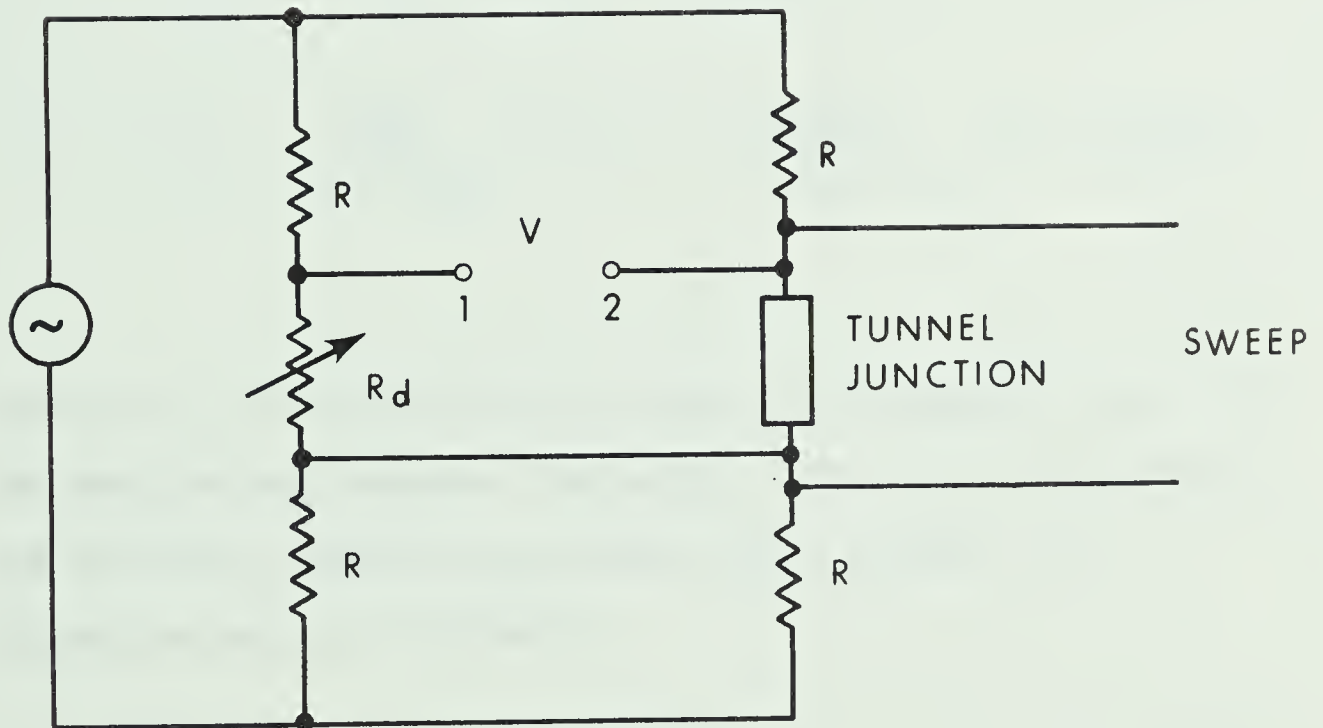
A system using a combination of harmonic detection and bridge techniques (Adler and Jackson, 1966) suitably interfaced to an online mini-computer facility for an analog and digital recording was used in obtaining the relevant information on tunnel junctions. These are the dynamical conductance $\sigma = dI/dV$ and its derivative $d\sigma/dV = d^2I/dV^2$. The principle of harmonic detection method can be understood by considering fig. 3.3.

In this circuit the tunnel junction serves as one arm of an ac Wheatstone bridge, the other arm being a variable resistor R_d . Assuming that the bridge is close to its balance the current through its arms is nearly identical. In the voltage region where the tunnel junctions are investigated, they behave as weakly



Fig. 3.3

Simplified bridge configuration





nonlinear passive elements. If the small current modulation amplitude δ is kept constant, then the voltage V across the junction can be written in terms of a Taylor's series

$$V(I) = V(I_0) + \left(\frac{dV}{dI}\right)_{I_0} \delta \cos \omega t + \frac{1}{2} \left(\frac{d^2V}{dI^2}\right)_{I_0} \delta^2 \cos^2 \omega t + \dots \quad (3.4)$$

or

$$V(I) = V(I_0) + \left(\frac{dV}{dI}\right)_{I_0} \delta \cos \omega t + \frac{1}{4} \left(\frac{d^2V}{dI^2}\right)_{I_0} (1 + 2 \cos 2\omega t) + \dots \quad (3.5)$$

where $V(I_0)$ is the DC-bias across the junction and ω is the modulating angular frequency. The voltage across the variable resistor R_d which has a linear I-V characteristics is given by

$$V_d = (I_0 + \delta \cos \omega t) R_d \quad (3.6)$$

Thus the difference in potential between points 1 and 2, V_{12} , has components at the modulating frequency ω and its various harmonics. The signal at the fundamental frequency, $V_{12}(\omega)$, is proportional only to the departure of the dynamic resistance $\left(\frac{dV}{dI}\right)_{I_0}$ from R_d and the second harmonic component, $V_{12}(2\omega)$, is proportional to $\left(\frac{d^2V}{dI^2}\right)_{I_0}$. Both these components are measured by means of a phase sensitive

detector.

$$V_{12}(\omega) = \delta [R_d - (\frac{dV}{dI})_{I_0}] \cos \omega t \quad (3.7)$$

$$V_{12}(2\omega) = \frac{1}{4} \delta^2 (\frac{d^2V}{dI^2})_{I_0} \cos 2\omega t \quad (3.8)$$

A direct calibration of $\frac{dV}{dI}$ curve enables the computation of the dynamical conductance $\sigma = \frac{dI}{dV}$. Ideally, the second derivative $\frac{d^2I}{dV^2} = \frac{d\sigma}{dV}$ is then calculated using the identity:

$$\frac{d^2I}{dV^2} = -\sigma^3 \cdot \frac{d^2V}{dI^2} \quad (3.9)$$

The presence of a second harmonic distortion in the modulation supply complicates the above relation. This necessitates a use of a different numerical method in calibrating $\frac{d\sigma}{dV}$. The mathematical details of the analysis of this problem are given in Appendix I with an earlier version of our data acquisition system. The present system which employs an online mini-computer and its peripherals allows a fast evaluation of the incoming data. The complete description of the new data acquisition system was given in a technical report (Adler, Straus, 1974).

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that this is essential for ensuring transparency and accountability in the organization's operations.

2. The second part outlines the specific procedures and protocols that must be followed when recording transactions. This includes details on how data should be collected, stored, and reviewed to ensure its integrity and reliability.

3. The third part addresses the role of technology in streamlining the record-keeping process. It highlights the benefits of using specialized software and digital tools to reduce manual errors and improve efficiency.

4. The fourth part discusses the importance of regular audits and reviews to verify the accuracy of the records. It stresses that these checks are necessary to identify any discrepancies or potential areas of improvement.

5. The fifth part provides guidance on how to handle sensitive information and ensure its confidentiality. It outlines the necessary safeguards and access controls to protect the organization's data from unauthorized access or disclosure.

6. The sixth part covers the legal and regulatory requirements that govern record-keeping practices. It ensures that the organization remains compliant with all applicable laws and standards.

7. The seventh part discusses the importance of training and education for staff involved in the record-keeping process. It emphasizes that ongoing learning is necessary to keep up with the latest best practices and technological advancements.

8. The eighth part provides a summary of the key points discussed throughout the document. It reiterates the importance of a robust record-keeping system for the organization's long-term success and sustainability.

9. The final part of the document offers concluding remarks and a call to action, encouraging all staff members to take ownership of their role in maintaining accurate and reliable records.

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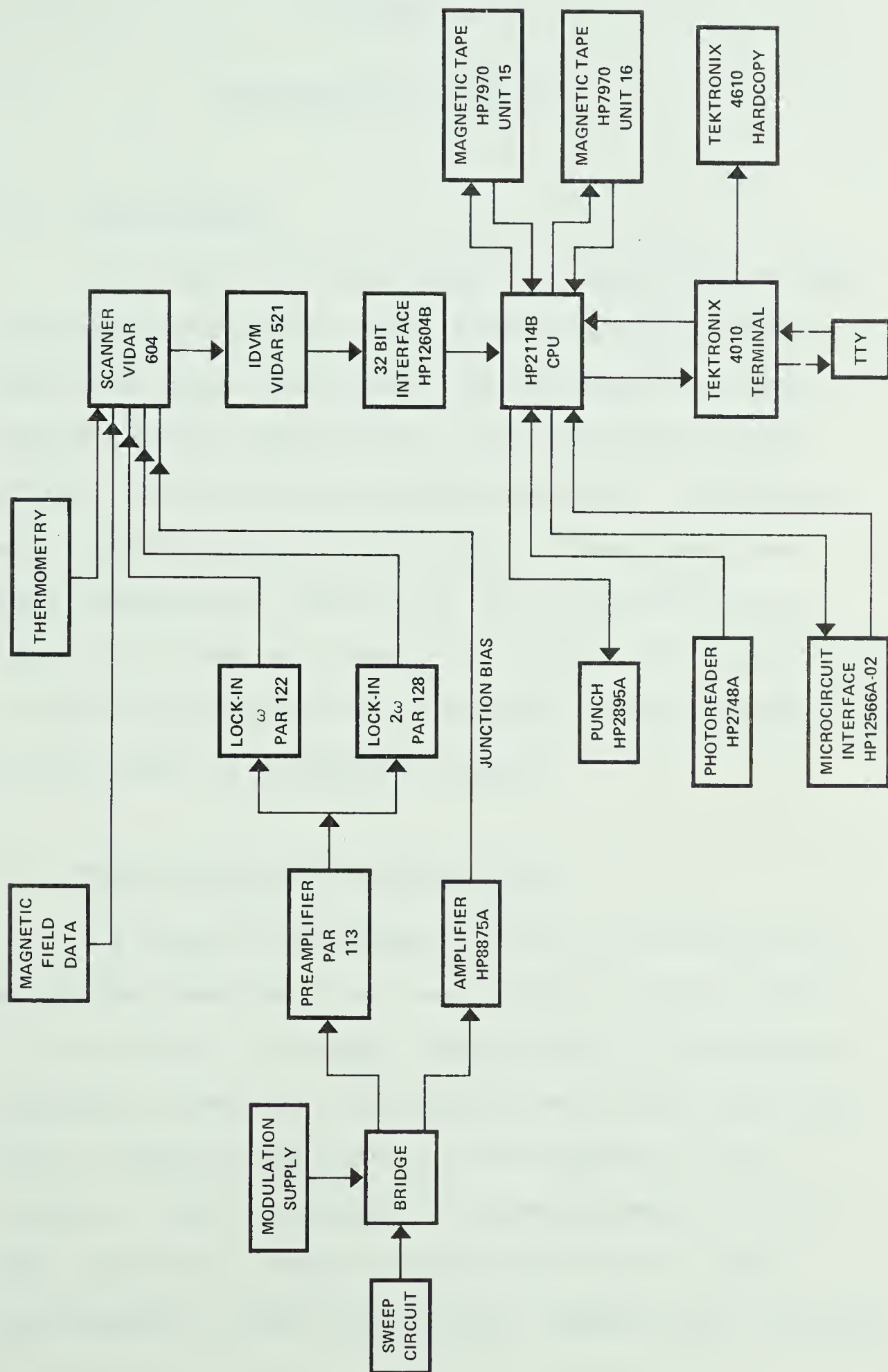
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Fig. 3.4

Schematic diagram of the data acquisition
system



CHAPTER 4

EXPERIMENTAL RESULTS

4.1 Introduction

To test the theory with the experiment we have prepared a series of tunnel junctions using different metals as their electrodes. The thickness of these ranged between 500-50000 Å. The insulating layers of the junctions were prepared either by oxidation or nitrification (for Mg only). Some junctions were deliberately doped with oil to reduce the probability of making a sample with spurious oscillations in their characteristics. Junctions having these, will be discussed in a separate chapter.

4.2 The Problem of the Background

A typical measurement of the conductance of a Mg/oil/Mg junction to a 5 meV range is shown in fig. 4.1 for several different temperatures. As the temperature increases, the conductance minimum decreases with a simultaneous loss in the sharpness of the anomaly. The second derivative measurement for the same junction is shown in the next figure. Here, the maximum of $d\sigma/dV$ with higher temperatures decreases



Fig. 4.1

Temperature dependent conductance
for a Mg/Mg junction.

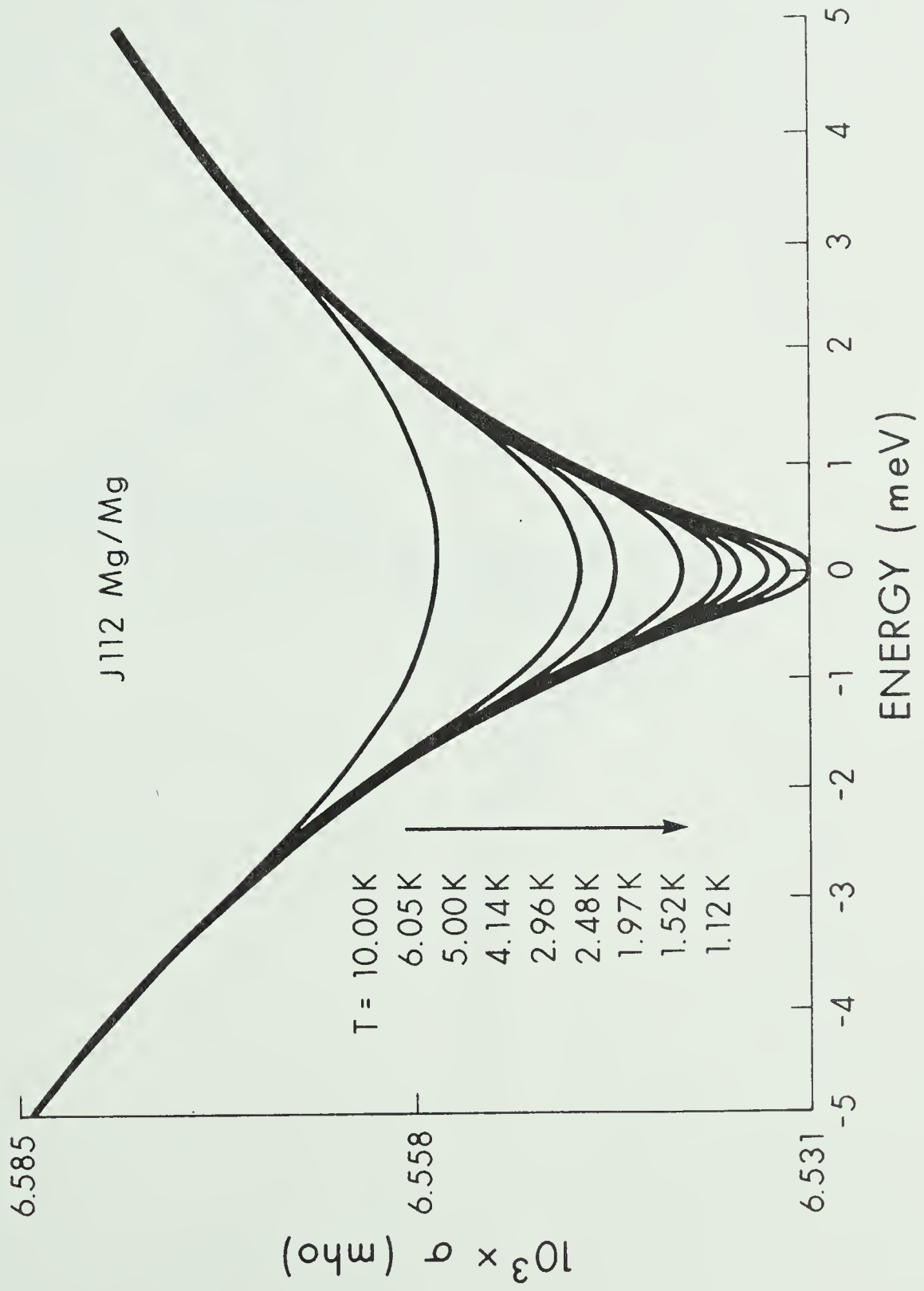
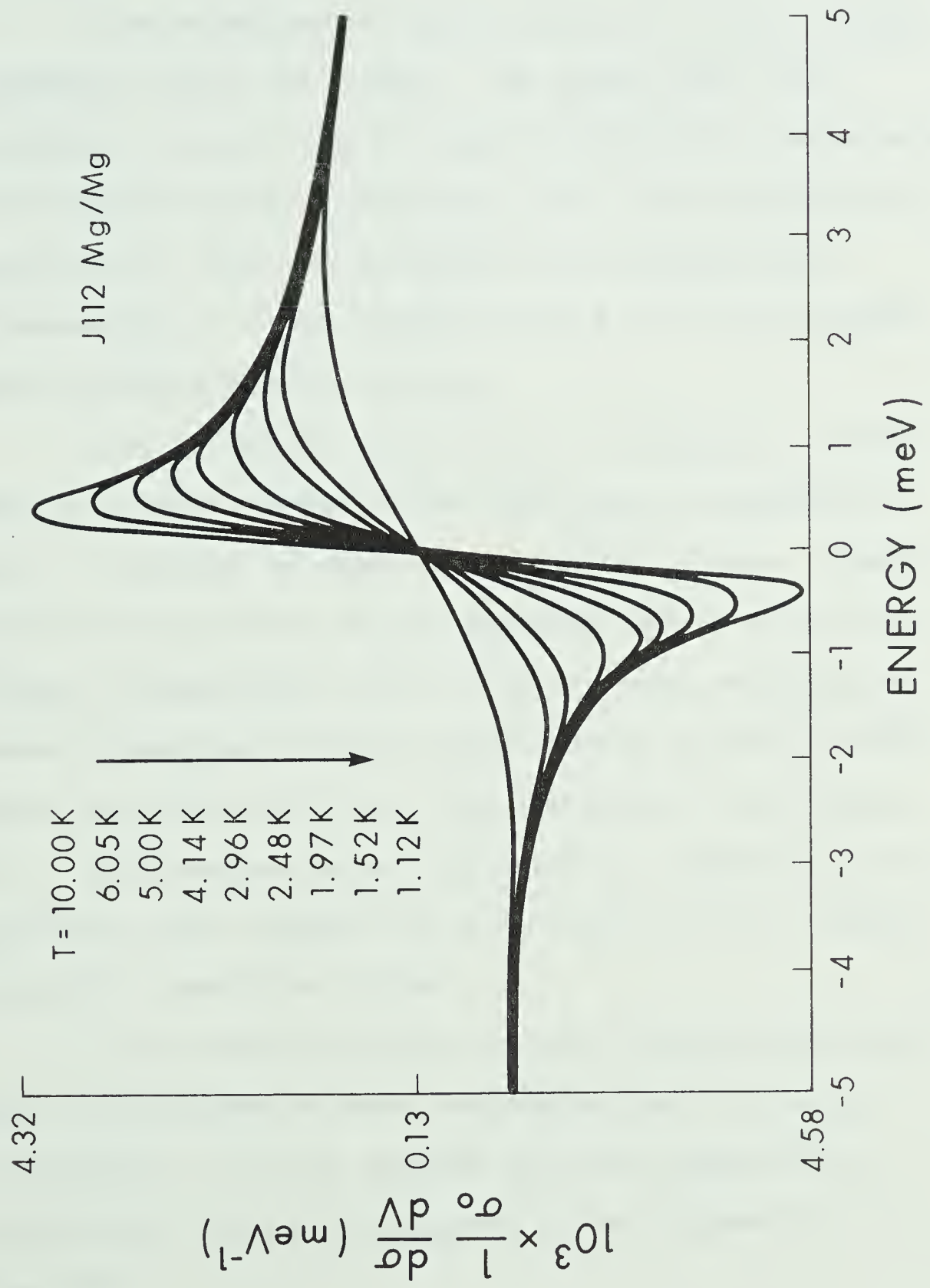






Fig. 4.2

Temperature dependent normalized
derivative of the conductance for
a Mg/Mg junction.





(for a positive applied bias) while its position shifts to a higher voltage.

The conductance curve in fig. 4.1 has a slight asymmetry about the origin. We assume that this asymmetry arises from the ideal background conductance as discussed earlier (section 2.1). To eliminate the background, which we consider to be temperature independent at least between 1-10 K, we have adopted the following two procedures.

Let us first recall fig. 2.6, where we notice that at higher temperatures, the dip in conductance due to blocking is essentially equal to zero. Therefore by subtracting the conductance measured at the highest temperature (10 K) from the ones measured at lower temperatures where the blocking is still effective, we can isolate the pure "blocking conductance $\delta\sigma$ ". This technique was successfully applied for the junction shown earlier. Fig. 4.3 and fig. 4.4 illustrate the resulting curves.

For junctions where the high temperature curve was not obtained we have considered the following alternative: Let us suppose that the experimental conductance may be represented by an expression of the form

$$\sigma(V) = \sigma_0 + \sigma_1 V + \sigma_2 V^2 + \delta\sigma(V, T) \quad (4.1)$$

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Fig. 4.3

Temperature dependence of the blocking conductance for a Mg/Mg junction after subtracting the background.

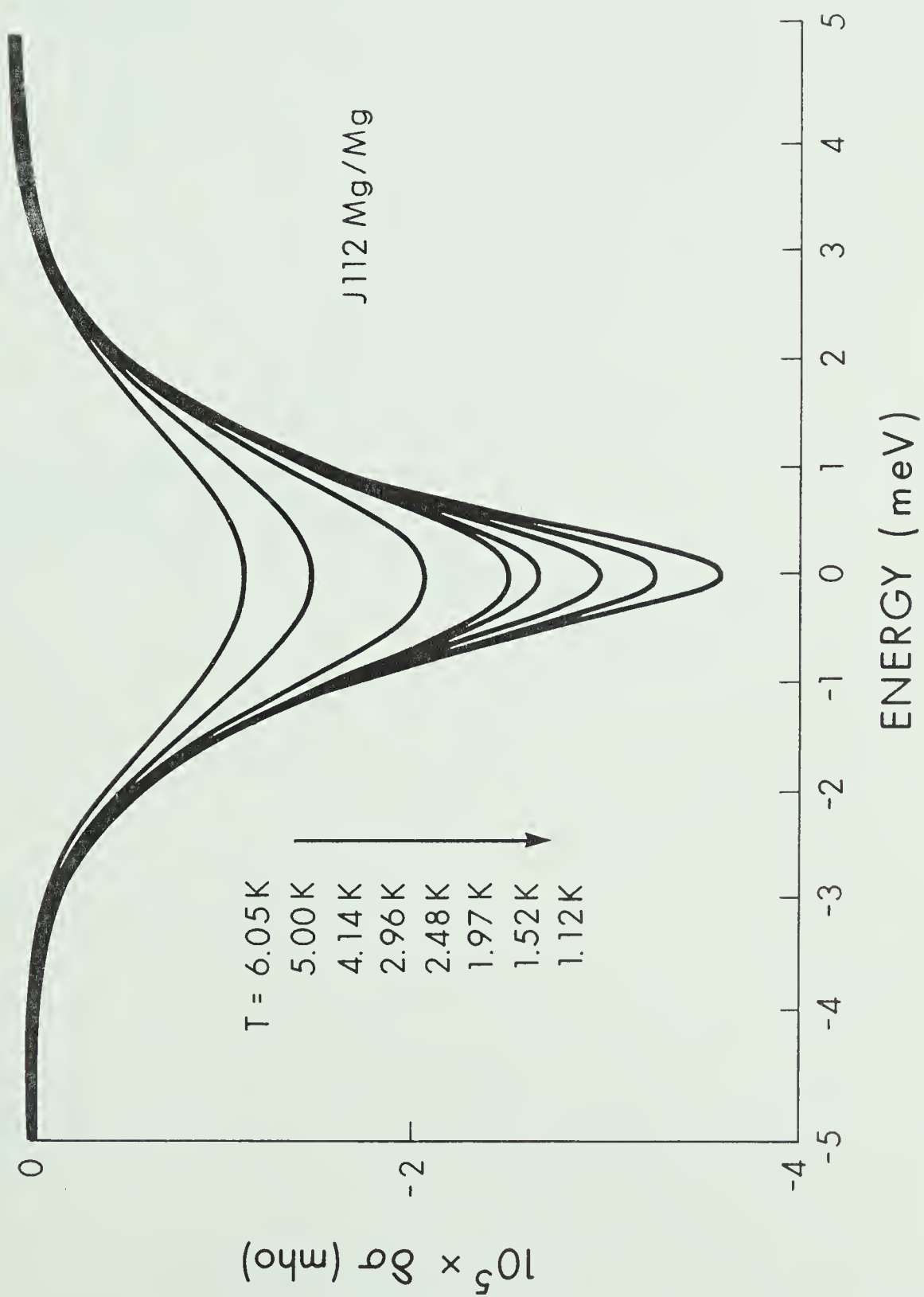
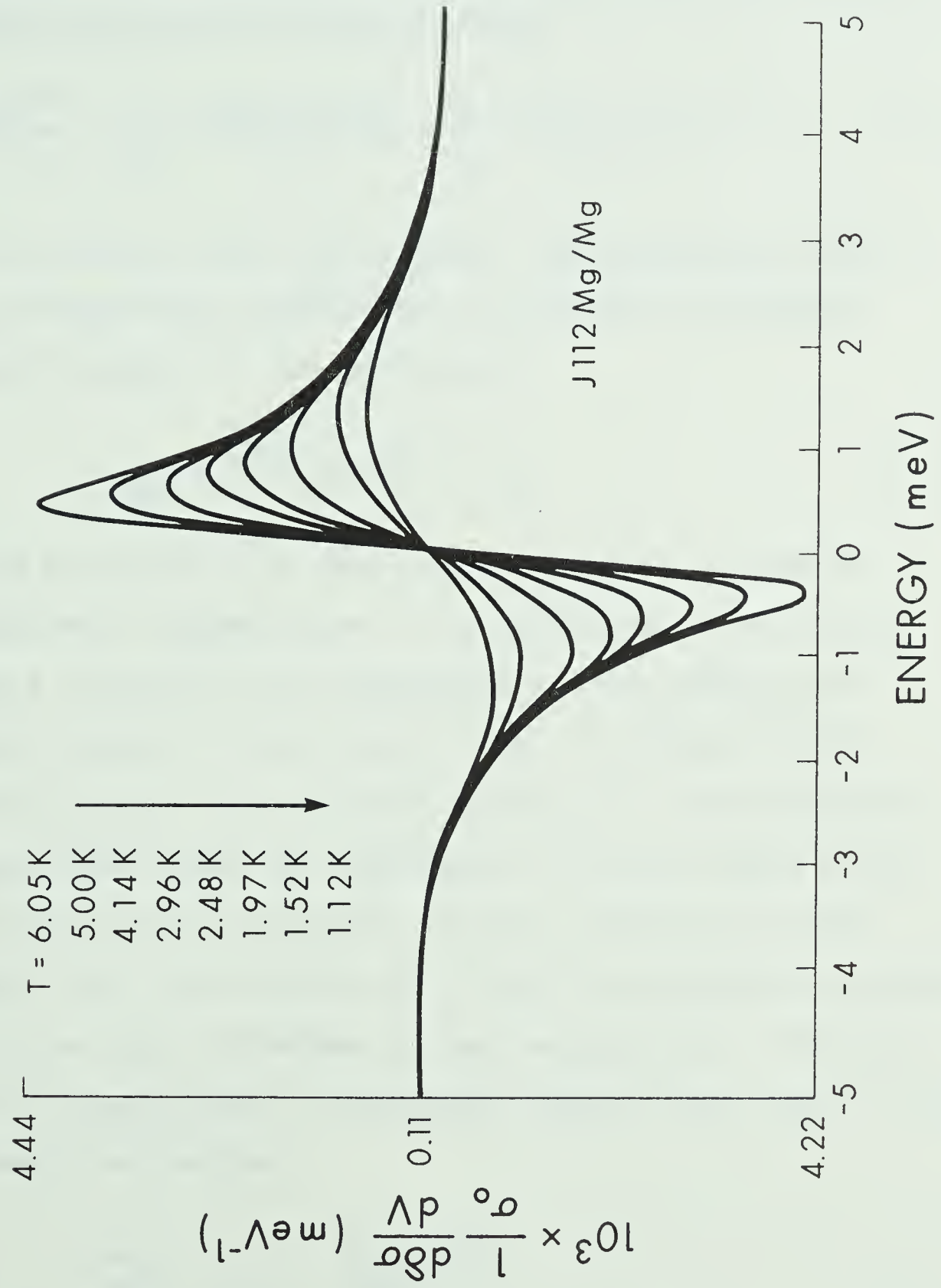






Fig. 4.4

Temperature dependence of the
normalized derivative of the blocking
conductance for a Mg/Mg junction after
subtracting the background.



where the first three terms constitute the ideal temperature independent background. Then by taking the even part of the conductance

$$\frac{\sigma_e(V)}{\sigma_o} = \frac{1}{\sigma_o} \left(\frac{\sigma(V) + \sigma(-V)}{2} \right) = \frac{\sigma_2}{\sigma_o} V^2 + \frac{\delta\sigma}{\sigma_o} (V_1 T) + 1 \quad (4.2)$$

We eliminate the linear term. The assumption that σ_1 is temperature independent is verified by forming the odd part of the conductance

$$\sigma_{\text{odd}} = \frac{\sigma(V) - \sigma(-V)}{2} = \sigma_1 V \quad (4.3)$$

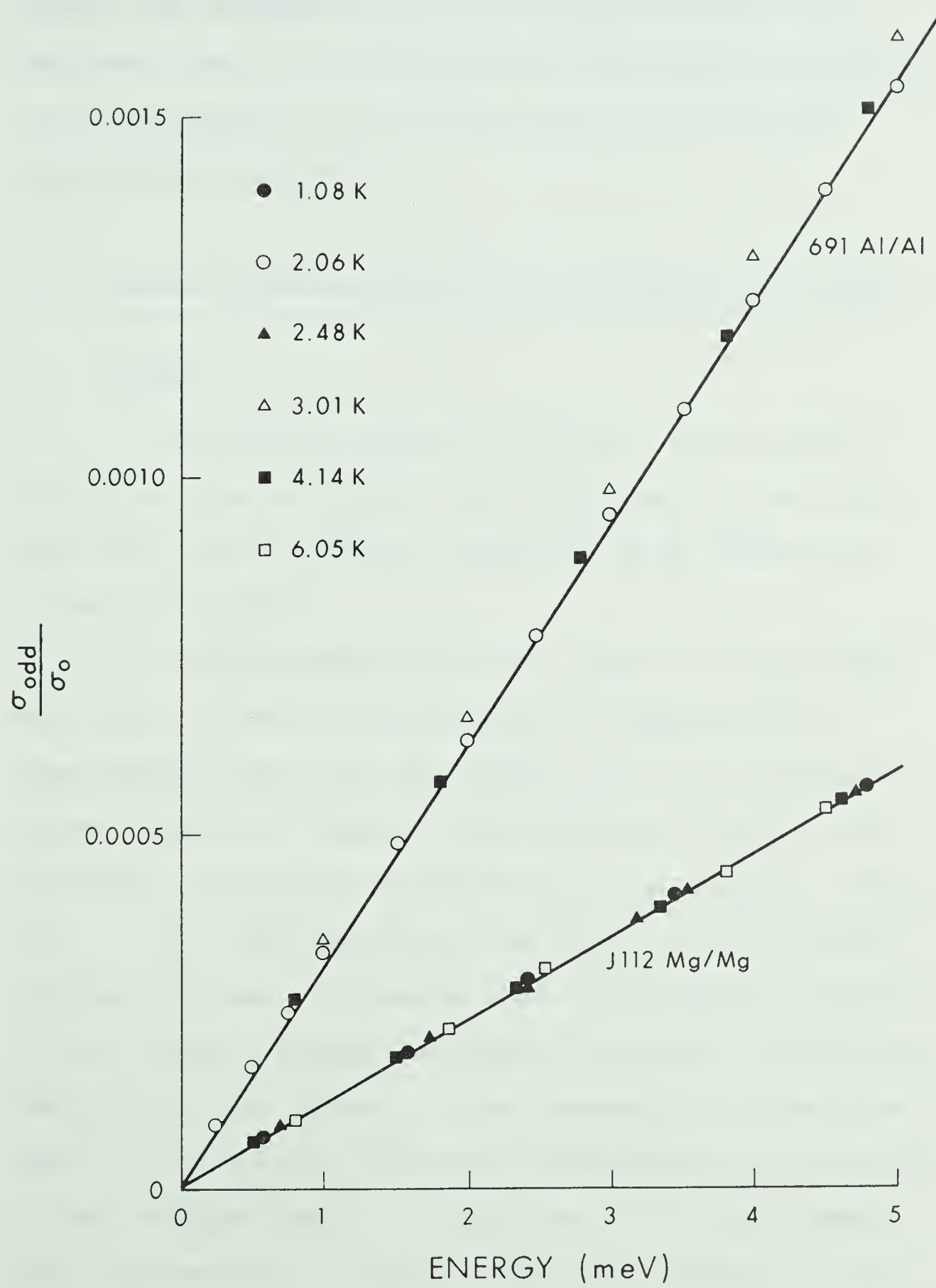
and plotting it as function of the bias voltage for different temperatures. The resulting curve should be a straight line independent of the temperature. This really is the case, as fig. 4.5 demonstrates. To eliminate the quadratic term $\sigma_2 V^2$, a more detailed knowledge about the background is needed which unfortunately we do not have. We can, however, use the fact that the blocking at 4-5 meV is negligible because of the short lifetimes of the excitations. Therefore it is appropriate to subtract from the even part of the second derivative

$$\frac{d\sigma_e}{dV} = 2\sigma_2 V + \frac{d\delta\sigma(V,T)}{dV} \quad (4.5)$$



Fig. 4.5

Experimental odd conductance





a line, passing through the origin, with a slope which brings the measured $d\sigma_e/dV$ to zero at 4-5 meV. We estimate that this technique may introduce at the most a 5% uncertainty in the determination of the peak magnitudes in $d\sigma_e/dV$.

4.3 General Considerations in Extracting τ_B , τ_i and τ_{drift}

A successful theory of the zero bias anomaly should be able to predict the lineshape of the conductance dip and its general behaviour with temperature or magnetic field.

Let us consider first the case of a zero magnetic field. The usual procedure in comparing the experimental data with the theory is to fit the measured curve at a fixed temperature and extract the necessary parameters characterizing the anomaly. These are τ_B - the tunneling time and τ_i - the impurity scattering time. We assume that the coupling strength of the electron phonon interaction is known beforehand. Having obtained τ_B and τ_i , the theoretical curves are then calculated for different temperatures and compared to the measured ones. In practice, it is more sensitive and accurate to fit the zero bias anomaly to the experimentally determined derivative of the even part

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of the conductance $\frac{1}{\sigma_0} \frac{d\delta\sigma_e}{dV}$. The curve is fitted with respect to the peak height and its peak position in terms of Γ and the ratio of τ_i/τ_B . For the sake of completeness we rewrite eq. (2.30) in these terms (assuming that $\alpha^2_F = a_1\omega$)

$$\frac{1}{\sigma_0} \delta\sigma_e = - \frac{2\tau_i \cdot \Gamma_1}{\tau_B} \int_0^\infty \frac{dx}{(e^x+1)(e^{-x}+1)} \left[\frac{1}{(\Gamma_1 + (xk_B T + eV)^2 + (\pi k_B T)^2)} + \frac{1}{(\Gamma_1 + (eV - xk_B T)^2 + (\pi k_B T)^2)} \right]. \quad (4.6)$$

The derivative of even conductance is given as

$$\frac{1}{\sigma_0} \frac{d\delta\sigma_e}{dV} = \frac{4\tau_i \Gamma_1 e}{\tau_B} \int_0^\infty \frac{dx}{(e^x+1)(e^{-x}+1)} \left[\frac{(xk_B T + eV)}{(\Gamma_1 + (xk_B T + eV)^2 + (\pi k_B T)^2)^2} + \frac{(eV - xk_B T)}{(\Gamma_1 + (eV - xk_B T)^2 + (\pi k_B T)^2)^2} \right]. \quad (4.7)$$

When writing the above equations we have again assumed that the junction is symmetric with respect to its relaxation processes and tunneling times. This simplifying assumption, as well, was used in the analysis of the experimental data. From the theoretical point of view, it is hard to justify this, even for samples prepared with the same electrodes, having the same thickness. Generally, the films can have different

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grain sizes and imperfections. In addition, the two interface planes adjoining the insulating layer can be contaminated with different impurities. This all, leads to a tunnel junction with non-symmetrical tunneling and scattering times. Considering eq. (2.30) we should then write the part enclosed in brackets as

$$\frac{1}{\tau_{B1}} \left(\frac{1}{(\Gamma_1^1 + \epsilon^2 + (\pi k_B T)^2)} + \frac{\tau_{B1}}{\tau_{B2}} \cdot \frac{a_1^1}{a_1^2} \frac{1}{(\Gamma_1^2 + \epsilon^2 + (\pi k_B T)^2)} \right) \quad (4.8)$$

from which it follows that generally we can use three parameters Γ_1^1 , Γ_1^2 and λ

$$\lambda = \frac{\tau_{B1}}{\tau_{B2}} \cdot \frac{a_1^1}{a_1^2} \quad (4.9)$$

to fit the temperature dependence of the experimental data. The fourth parameter τ_{B1} adjusts the peak amplitudes. With a three parameter fit we have to consider the interference between the two terms in (4.8) which can be responsible in creating an additional peak in $d\delta\sigma_e/dV$. Experimentally, the two peaks in $\frac{1}{\sigma_0} \frac{d\delta\sigma_e}{dV}$ were never observed. This does not, however, exclude the possibility of their insufficient separation and the small size of the second peak.

Numerical analysis (Teshima, 1974) indicates that the second derivative will not have the two peaks as long as

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$$\frac{\Gamma_1}{\Gamma_2} < 8 + \sqrt{90} \quad \text{at} \quad T = 0 \text{ K} .$$

Since the experimentally found parameter Γ ranged from $.4 \leq \Gamma \leq 2.(\text{meV})^2$, it is safe to assume that the condition above is always satisfied.

Nevertheless we have compared some of our data with the predictions of the theory using a three parameter fit. In general, there was no appreciable difference between this fit and the one obtained by assuming a symmetrical junction.

Furthermore, we assume that τ_{ep} , the relaxation time due to electron-phonon interaction is given by eq. (2.12). This is equivalent to an assumption that α^2_F behaves linearly for small excitation energies. The justification of this assumption is partly based on the preliminary results of measurements on Mg/Mg and Mg/Au junctions down to 0.3 K. The second derivative characteristics of these junctions have not shown kink in the vicinity of zero, whereas they would if α^2_F behaved quadratically for small energies (fig. 2.5). In addition, the theoretical fits using τ_{ep} derived on the basis of the linear α^2_F behaviour were superior to those obtained by τ_{ep} of eq. (2.13) and eq. (2.14).

The relaxation time τ_{drift} associated with the magnetic field measurements can be extracted only if both τ_i and τ_B are known. But these are obtained from

zero field measurements. The procedure is strictly valid for τ_B which is magnetic field independent. The results prove this assumption to be a correct one.

4.4. Comparison of the Theory with the Experiment

Let us first consider the results of the theory applied on the previously discussed Mg/Mg junction. in fig. 4.6, beside the experimentally determined data points, we show the behaviour of the theoretical curves for three different parameters $\Gamma = 0.4, 0.8, 1.2 \text{ meV}^2$. The peak amplitudes were normalized at 1 K. The dependence of the peak positions on the temperature is well fitted by a theoretical curve with $\Gamma = 0.4 \text{ meV}^2$. In this case, however, the peak amplitudes do not drop as fast as the theory would predict. The second extreme, $\Gamma = 1.2 \text{ meV}^2$, fits the peak amplitudes better at higher temperatures, whereas the peak positions lie below the theoretical curve. A reasonable compromise is to assume that $\Gamma = 0.8 \text{ meV}^2$ represents the best fit.

The theory then predicts a stronger temperature dependence of the peak amplitudes than experimentally observed. Correspondingly the peak positions are at lower biases than expected.

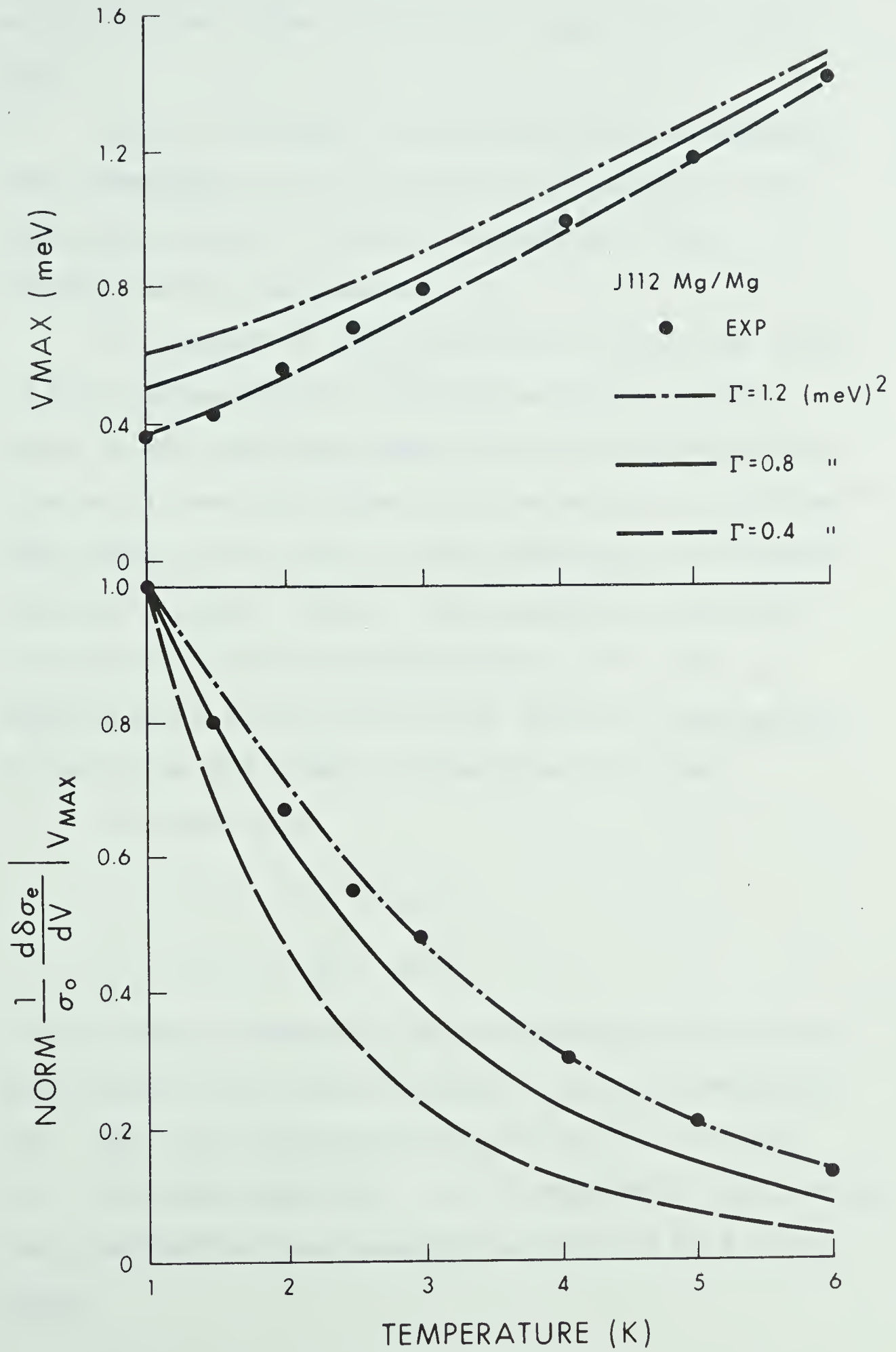
The reasons behind accepting $\Gamma = 0.8 \text{ meV}^2$ as the best fit will be more transparent when we consider the results of the experiments on other junctions. We

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Fig. 4.6

Comparison of the experimentally determined peak positions, $V_{\max}$ (upper diagram) and peak amplitudes, $\frac{1}{\sigma_0} \left. \frac{d\delta\sigma_e}{dV} \right|_{V_{\max}}$ (lower diagram) for a Mg/Mg junction at various temperatures with peak positions and peak amplitudes predicted by the theory.





will find that these conclusions apply equally for them.

With $\Gamma = 0.8 \text{ meV}^2$ we have plotted the temperature dependence of the blocking conductance at zero bias and compared it with the experiment (fig. 4.7) the data were normalized at 1 K.

To extract τ_i and τ_B we have to know the value of the electron-phonon coupling constant for Mg. Since to our knowledge there is no available information on it, we have taken it to be equal to $.0015 \text{ meV}^{-1}$. This value is one half of that published for aluminum (Carbotte, Dynes, 1968). This certainly introduces an uncertainty in the determination of τ_i and τ_B . Nevertheless, we feel that this choice is appropriate in obtaining the order of magnitudes involved.

We have then

$$\tau_i = 1.8 \times 10^{-10} \text{ sec}$$

$$\tau_B = 9.6 \times 10^{-8} \text{ sec}$$

Using these parameters we can compare the theoretical even part of the second derivative with the measured one. Fig. 4.8 illustrates the fit at $T = 1 \text{ K}$ and 3 K . The peak amplitude at 3 K reproduces well, while the experimental peak position is shifted to a lower value.

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Fig. 4.7

Comparison of the temperature dependent blocking conductance at zero bias for a Mg/Mg junction with the blocking conductance calculated from the theory.

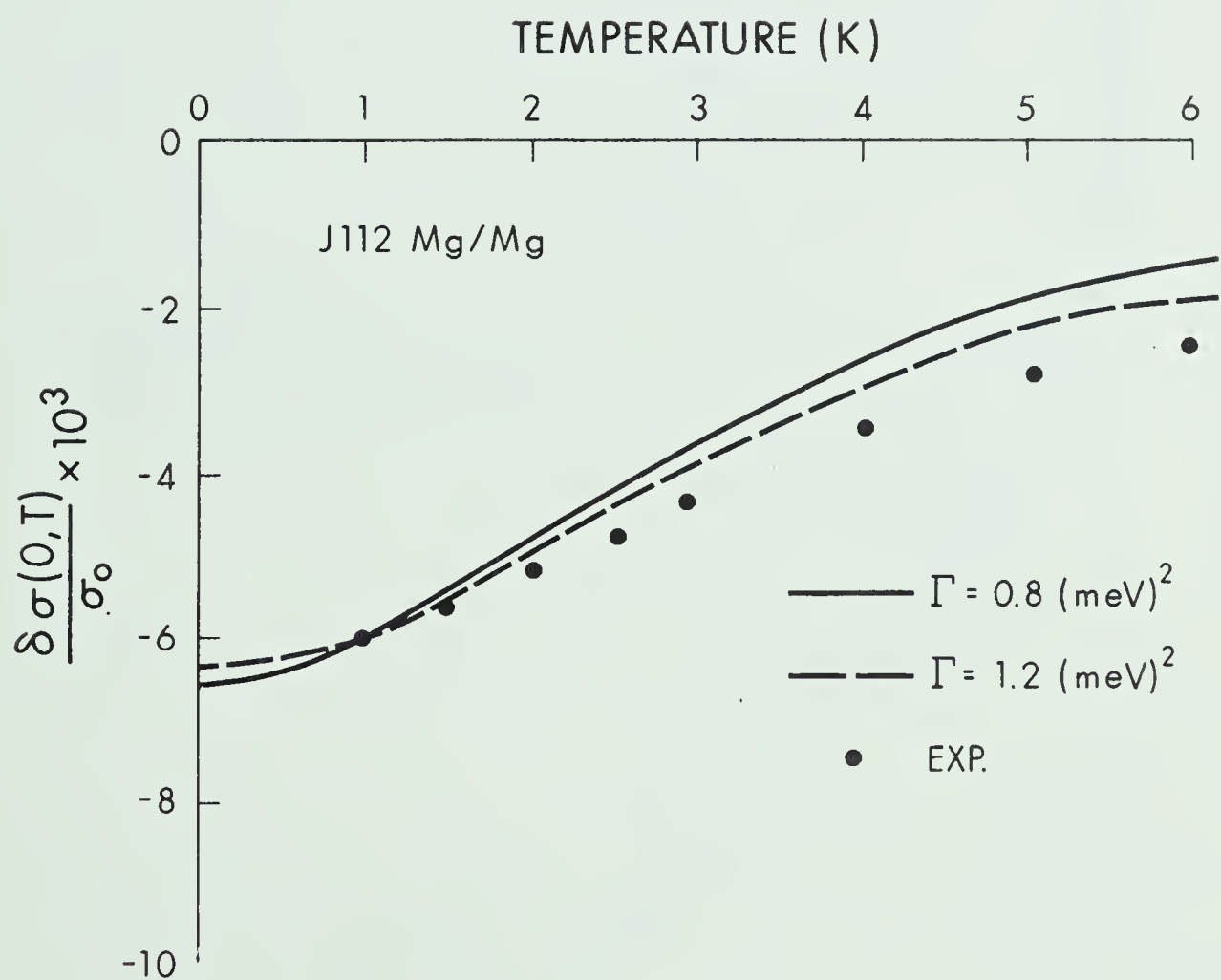
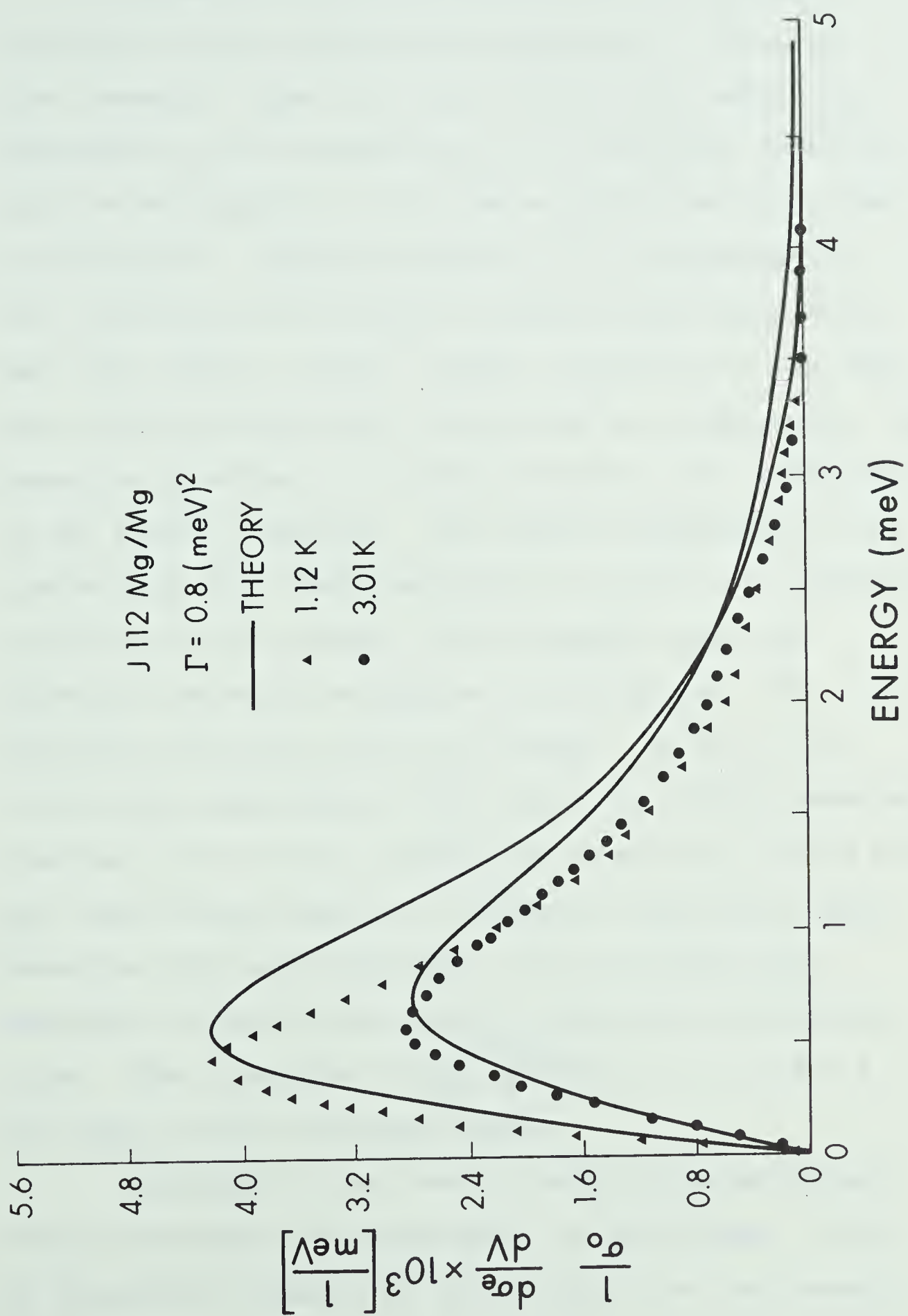






Fig. 4.8

Comparison of the experimentally determined $\frac{1}{\sigma_o} \frac{d\delta\sigma_e}{dV}$ for a Mg/Mg junction with $\frac{1}{\sigma_o} \frac{d\delta\sigma_e}{dV}$ predicted by the theory .





Replacing the top Mg layer by an Au counter-electrode has not altered the character of the zero bias anomaly. Figs. 4.9 and 4.10 show the temperature dependence of the conductance of two Mg/N₂/Au junctions. These were prepared on the same substrate with the same Au overlayer. Completing their initial measurement, the junctions were allowed to warm up while they still were kept under a vacuum. After a period of a few days, the junctions were again cooled down and remeasured. The annealing produced a 2.5 fold increase in the resistance of the tunnel junctions. The relative magnitude of the conductance dip, characteristic of the zero bias anomaly, however, has not changed. This documents that the relevant scattering mechanisms which deblock the tunneling electrons were not altered. In fig. 4.11 we show the experimental data for 85 B1 and B2 (annealed) together with the fit obtained by adjusting Γ to 0.6 meV². The theory again predicts a stronger temperature dependence for the peak amplitudes. As the temperature decreases the peak positions lie below the theoretical curve. The lineshapes of $\frac{1}{\sigma_0} \frac{d\delta\sigma_e}{dV}$ for $T = 1$ K and 3 K are shown in the following figure.

According to the theory, metals with infinitely thick electrodes are essentially in equilibrium. This is because the density of final states for the incoming

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Fig. 4.9

Temperature dependence of the zero bias
conductance anomaly for O85A Mg/N₂/Au

Mg = 30000 Å

Au = 2200 Å

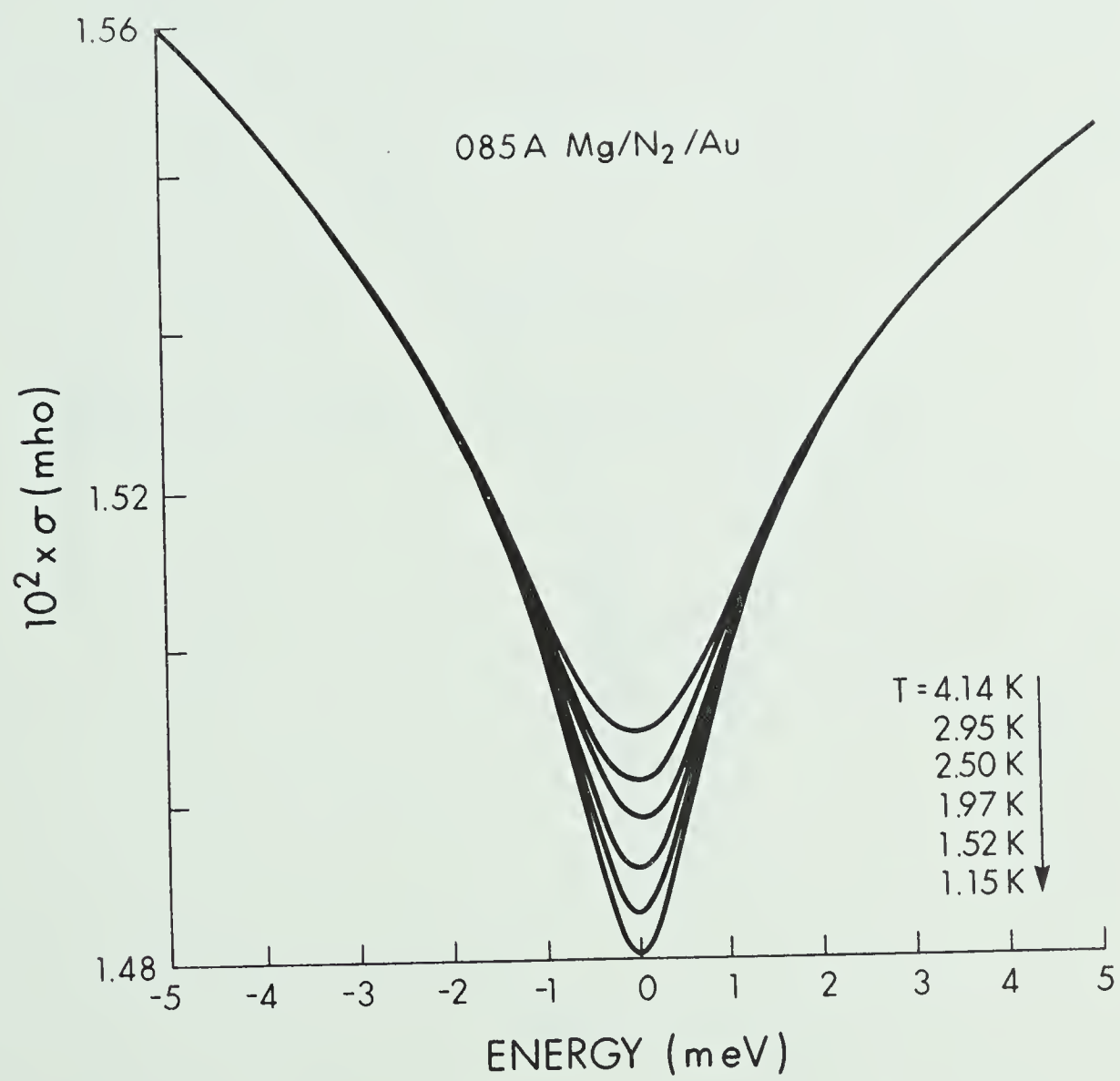






Fig. 4.10

Temperature dependence anomaly for 085B

Mg/N₂/Au

Mg = 3000 Å

Au = 2200 Å

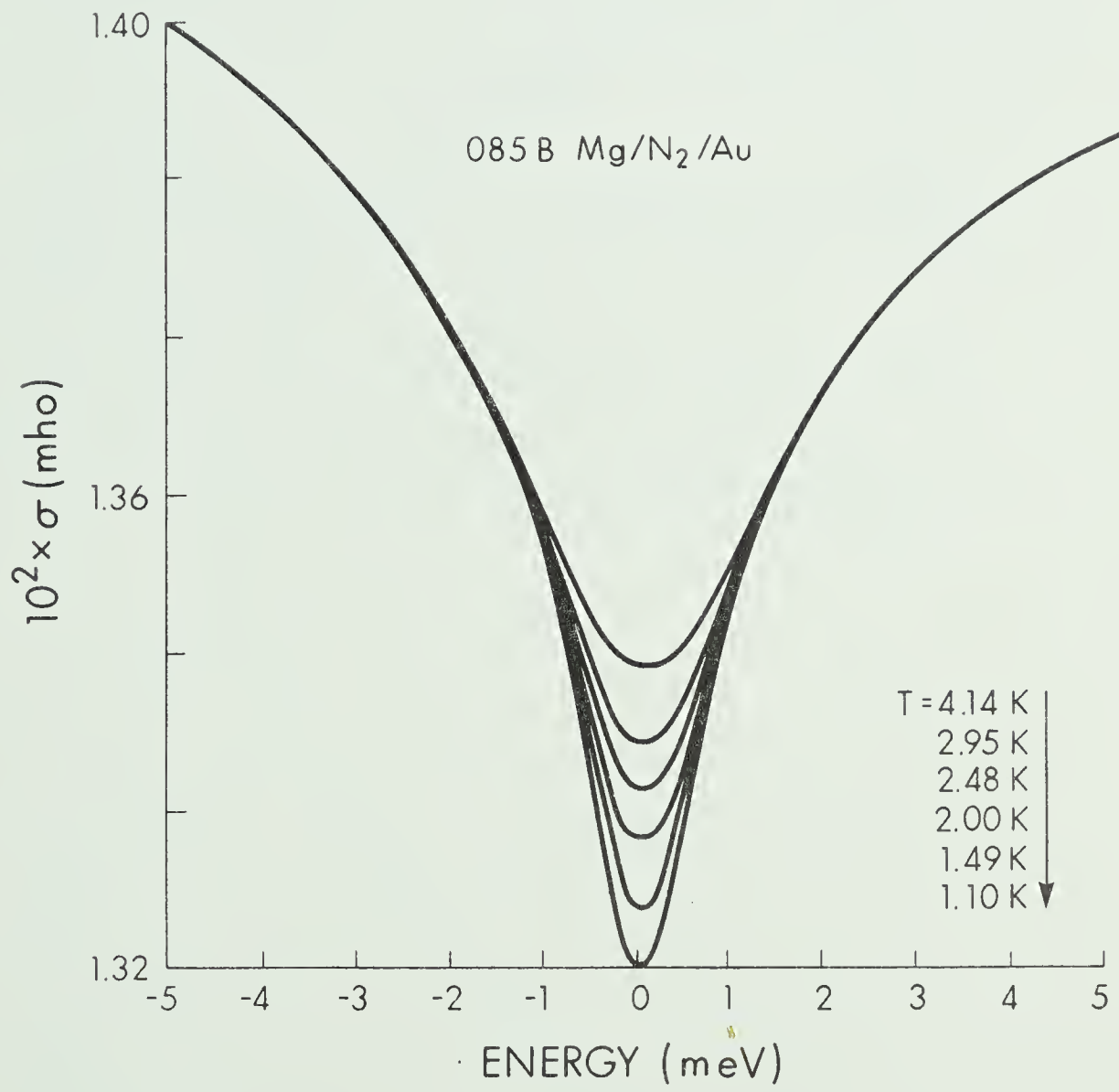






Fig. 4.11

Temperature dependence of peak positions, $V_{\max}$
(upper diagram) and peak amplitudes, $\frac{1}{\sigma_0} \left. \frac{d\delta\sigma_e}{dV} \right|_{V_{\max}}$
(lower diagram) of O85, before (B1) and after
(B2) annealing. The solid lines represent the
theoretical fit.

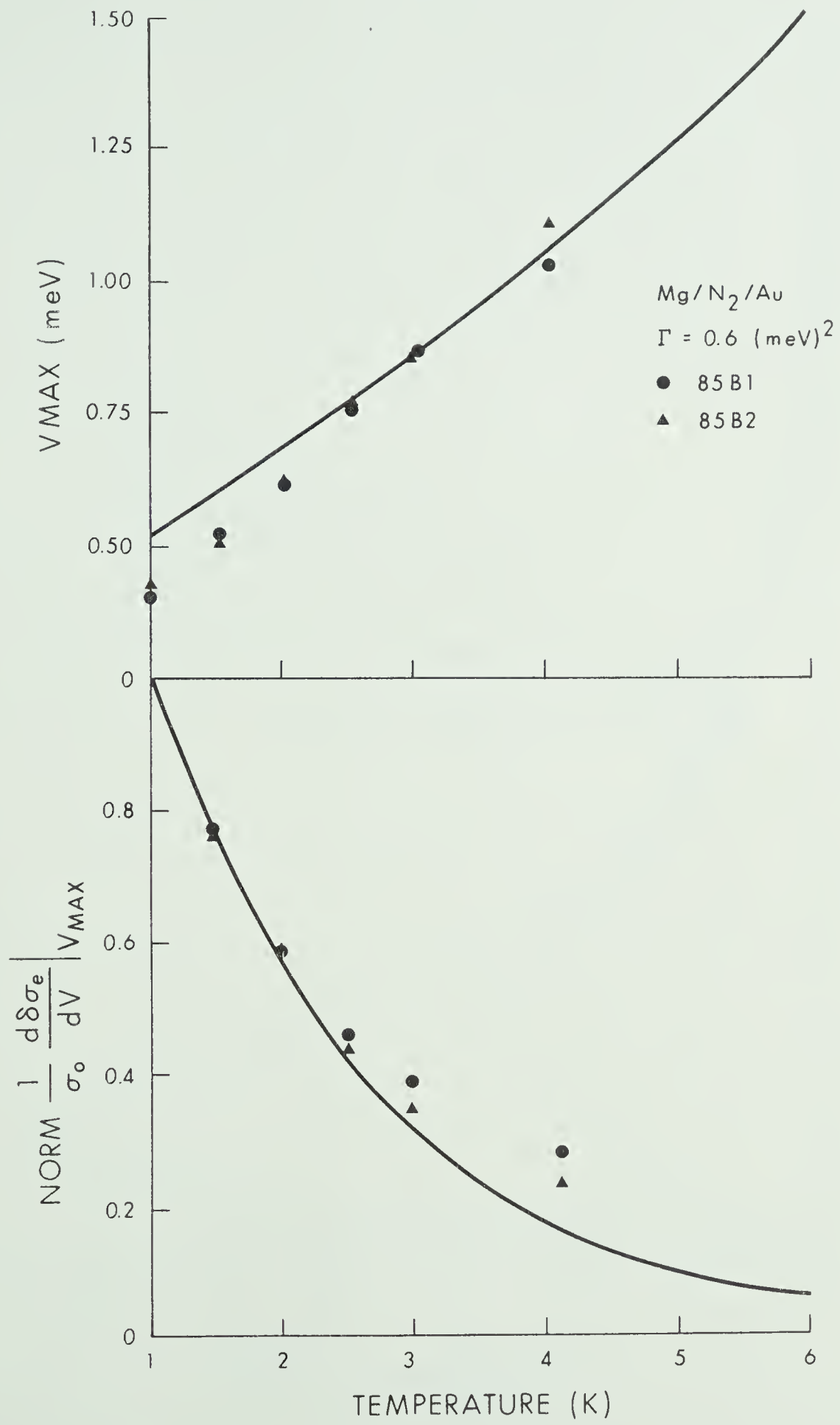
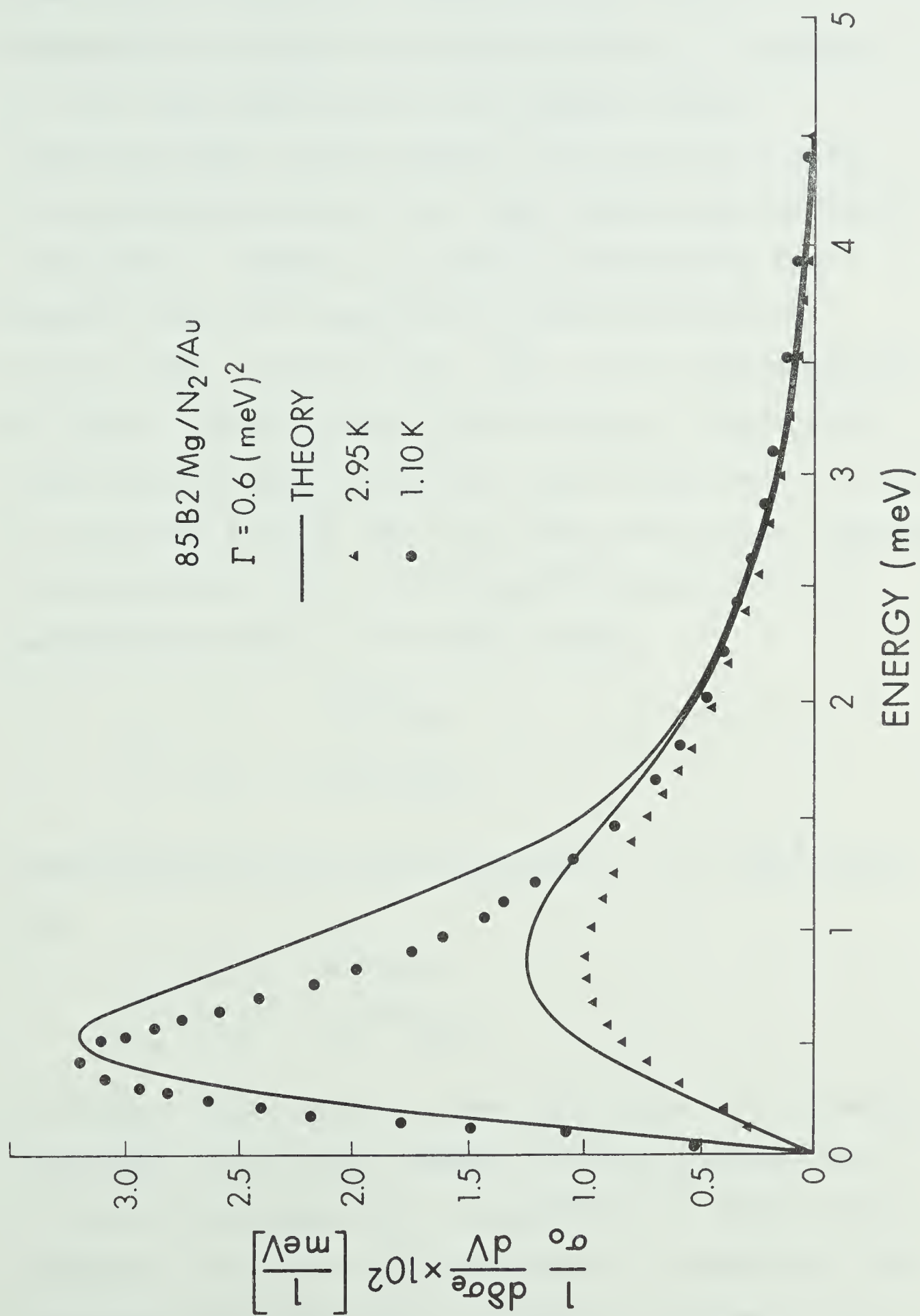






Fig. 4.12

Comparison of experimental and theoretical
 $\frac{1}{\sigma_0} \frac{d\delta\sigma_e}{dV}$ for O85B2, Mg/N₂/Au.



electrons is infinite. Mathematically, this is expressed by setting the tunneling time τ_B to infinity. To test this assertion we have prepared double junctions which had one common electrode and in which the counterelectrodes of the same material had different thicknesses. Samples so prepared consistently had smaller zero bias anomalies in junctions with the thicker film. Junctions 85A, 85B are the representative of these. The Au film was 2200 Å thick. The Mg electrode for the junction 85B was 3000 Å thick while for 85A it was 30000 Å thick (fig.4.13). The solid lines represent the theoretical fits. The "thinner" junction 85B was parameterized with $\Gamma = 0.6 \text{ meV}^2$, giving

$$\begin{aligned}\tau_B &= 1.3 \times 10^{-8} \text{ sec} \\ \tau_i &= 2.0 \times 10^{-10} \text{ sec.}\end{aligned}$$

The "thicker" junction was fitted with $\Gamma = 1.3 \text{ meV}^2$ yielding

$$\begin{aligned}\tau_B &= 1.0 \times 10^{-8} \text{ sec} \\ \tau_i &= 1.1 \times 10^{-10} \text{ sec.}\end{aligned}$$

Of course, these tests can give only qualitative answers. Meaningful quantitative numbers could be obtained only for metal electrodes with a character of a single grain throughout the entire film thickness. In practice, the evaporated films may grow in layers of different thick-

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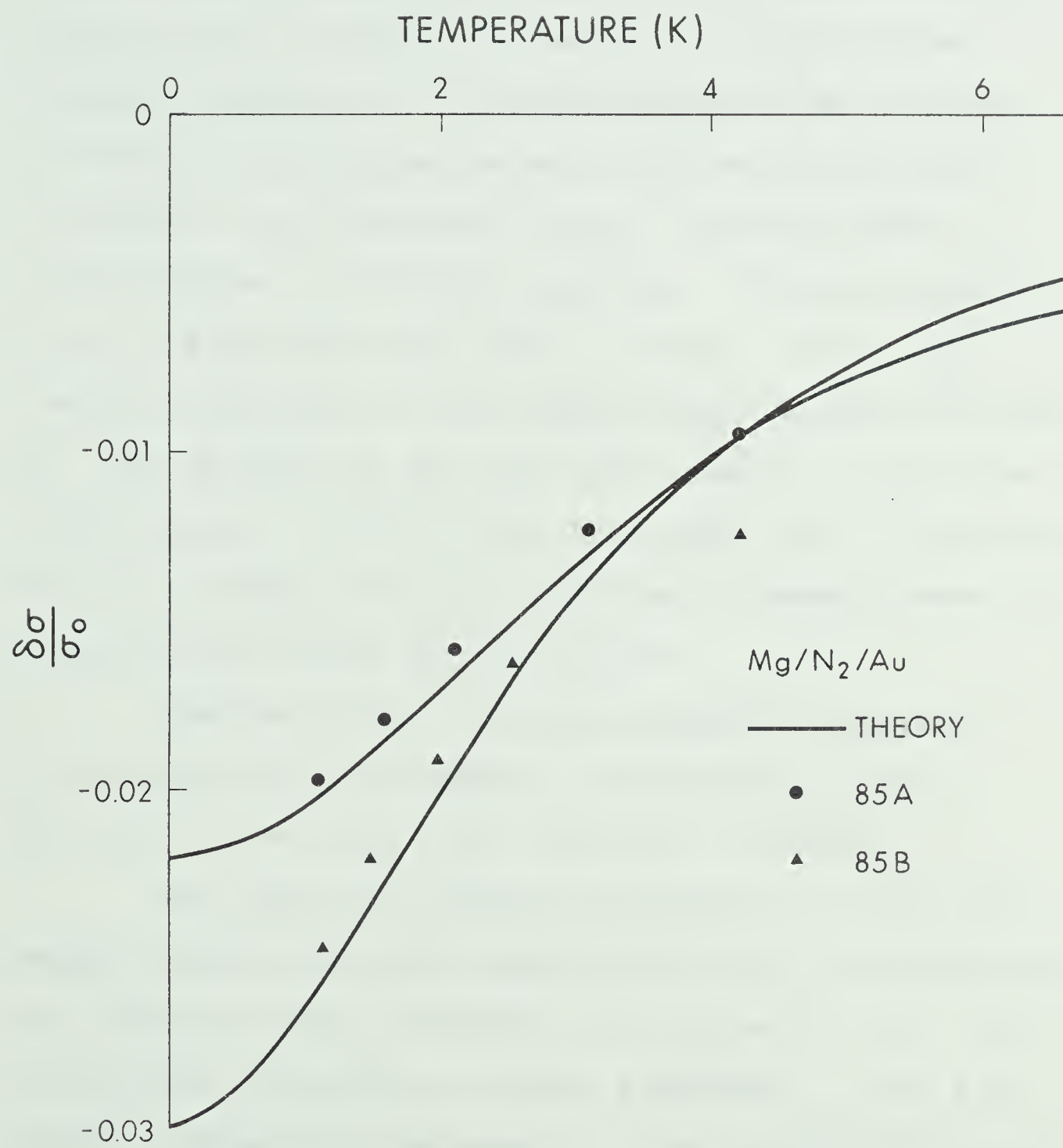
Fig. 4.13

Zero bias blocking conductance for two junctions with different thickness of metal electrodes.

(85A - Mg = 30000 Å, Au = 2200 Å)

(85B - Mg = 3000 Å, Au = 2200 Å).

The theoretical fit (solid line) for 085B was calculated with $\Gamma = 0.6 \text{ meV}^2$. 85A was fitted with $\Gamma = 1.3 \text{ meV}^2$.





ness and orientation. This then reduces the overall observable effect. The results of this discussion apply equally well to that part of the impurity relaxation time τ_i which is responsible for the diffuse boundary scattering. An investigation of Mg films by an electron microscope revealed that Mg crystallizes in grains, the thickness of which could be equal to the thickness of the whole specimen. This was probably true of films less than 1500 Å (Turner, 1974). The lateral dimensions of the grains ranged between 500-800 Å. The decrease of the zero bias anomaly in junctions with thicker (>1500 Å) films then shows that a fraction of the incoming electrons feels the increased number of grains grown across the whole film.

Similar results have been obtained on Mg/Au junctions having an oxide as its insulating layer. In fig. 4.14 we show a fit for such a junction.

The zero bias anomaly measurements on Mg/Au and Mg/Mg systems have been complemented with investigations on junctions having different electrodes (Pb, Al). We illustrate the results on Al/Al structures. Fig. 4.15 shows a temperature dependence of the conductance dip out on a previously published Al/Al junction (Trofimenkoff, et al, 1972). The data were fitted to the 3 K curve width



Figure 1.1

Figure 1.1 shows a graph of distance versus time for an object moving with constant speed. The line is a straight line passing through the origin, which indicates that the object starts at the origin and moves with a constant speed.

The slope of the line represents the speed of the object. The steeper the line, the greater the speed.

Figure 1.2 shows a graph of distance versus time for an object moving with constant acceleration.



Figure 1.2

Fig. 4.14

Comparison of the experimentally determined peak positions, $V_{\max}$ (upper diagram) and peak amplitudes, $\frac{1}{\sigma_0} \left. \frac{d\delta\sigma_e}{dV} \right|_{V_{\max}}$ (lower diagram) for a Mg/O/Au junction at various temperatures with peak positions and peak amplitudes predicted by the theory.

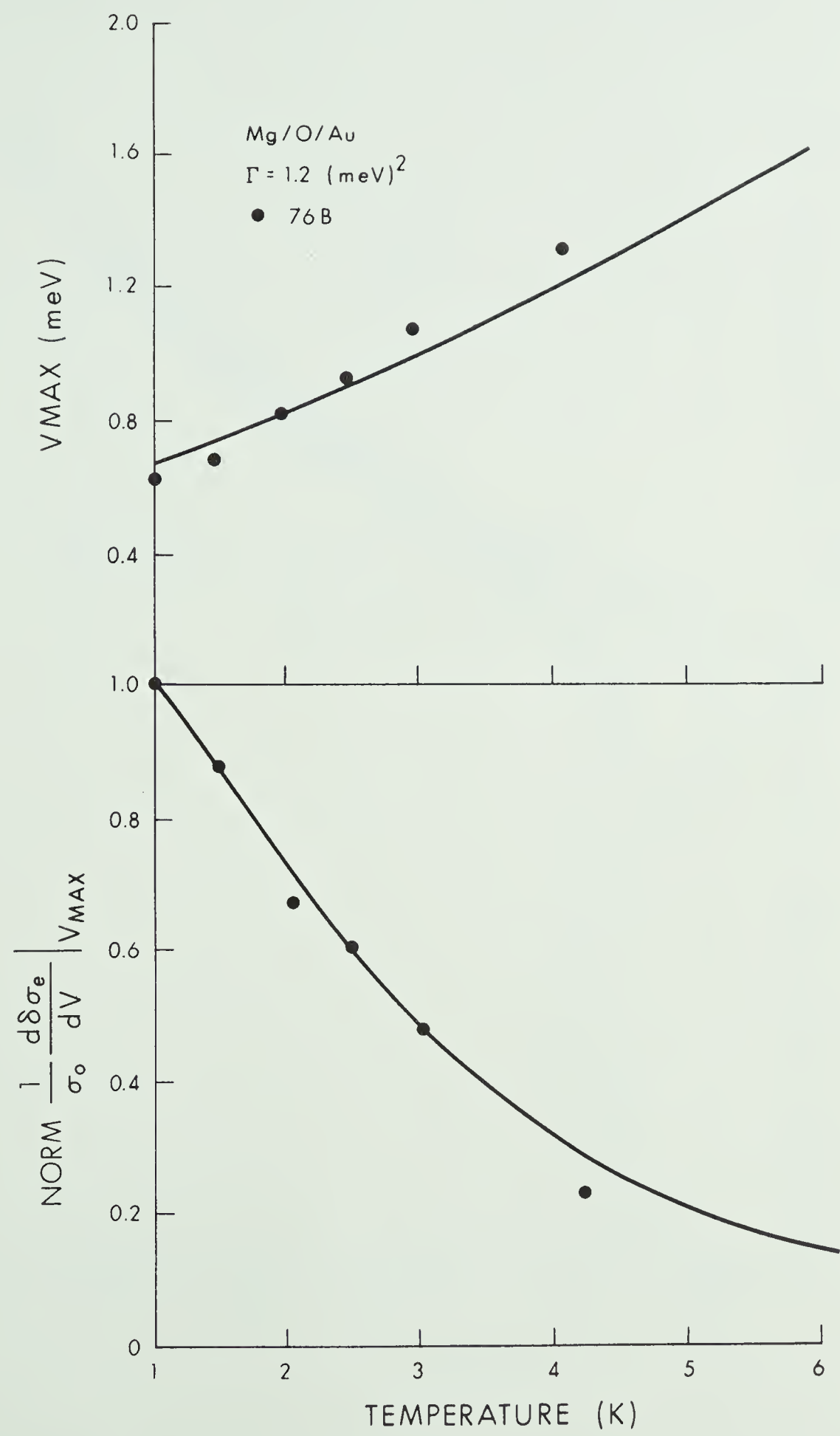
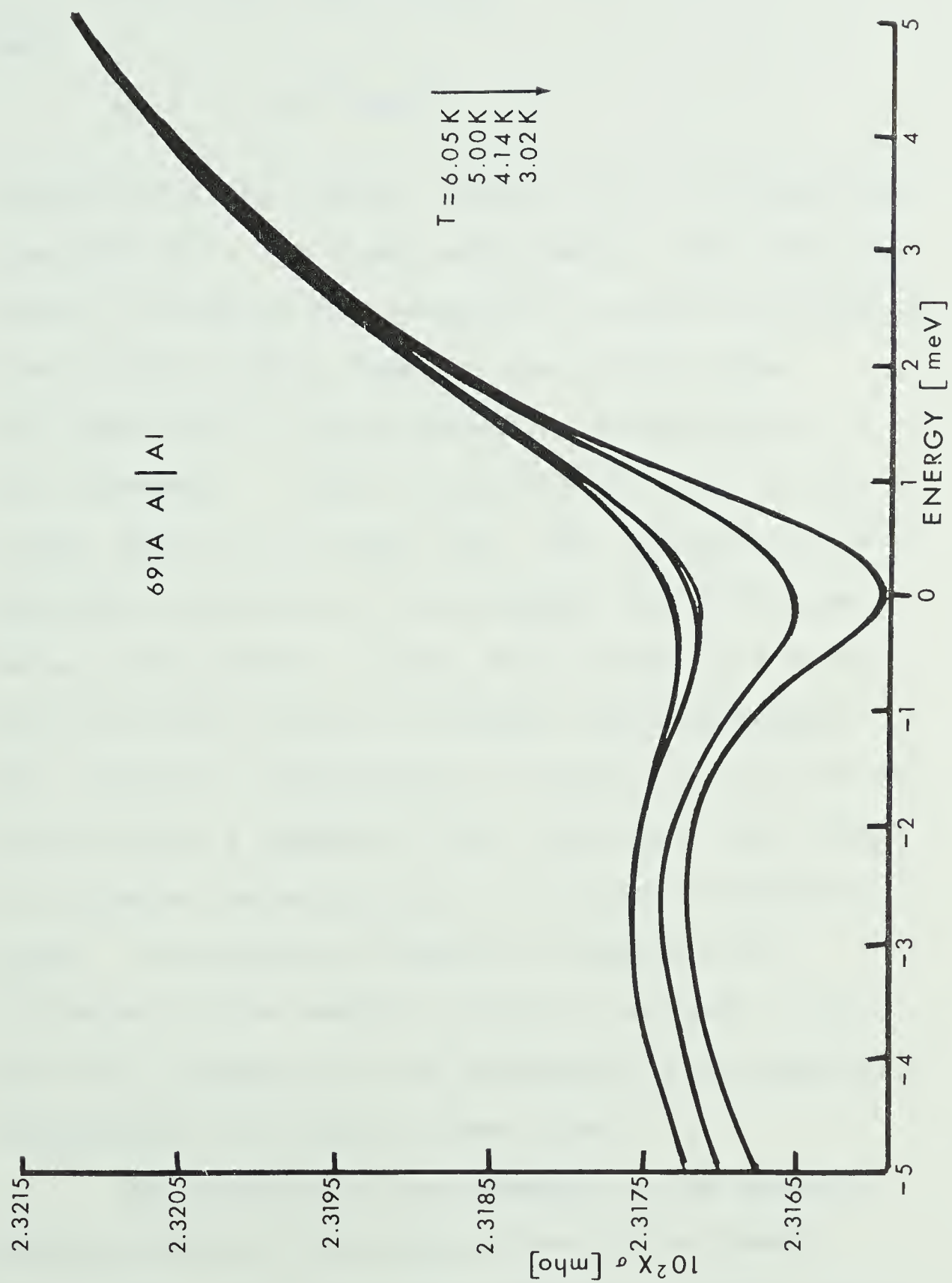




Fig. 4.15

Temperature dependent conductance
of an Al/Al junction.



$$\tau_B = 1.4 \times 10^{-7} \text{ sec}$$

$$\tau_i = 3.5 \times 10^{-10} \text{ sec}$$

and

$$a = 3 \times 10^{-3} \text{ meV}^{-1}$$

(Carbotte, Dynes, 1968). Figs. 4.16, 4.17 show the resulting fit. In these measurements care had to be taken to separate the decrease in conductivity due to the blocking effect from the one arising from the appearance of superconducting energy gap in the electrode. This is particularly true of thin films, where it is known that the transition temperature increases with decreasing film thickness. We show this effect in fig. 4.18, where at 2 K the Al film (680 Å thick) is already superconducting. The transition temperature of the bulk Al is 1.19 K. In principle a magnetic field could have been used to suppress the appearance of the superconducting phase. But since we wanted to eliminate the influence of the magnetic field on the size of the zero bias anomaly for the subsequent field dependence measurements this has not been done.

The results in the presence of the magnetic field agreed with the predictions of the theory (Sec. 2.5). They have been described earlier (Adler, et al, 1973) and are attached as an Appendix (Appendix II).

Fig. 4.16

Peak height (open circles) and peak position (full circles) vs temperature for an Al/Al junction. The solid line represents the theoretical fit.

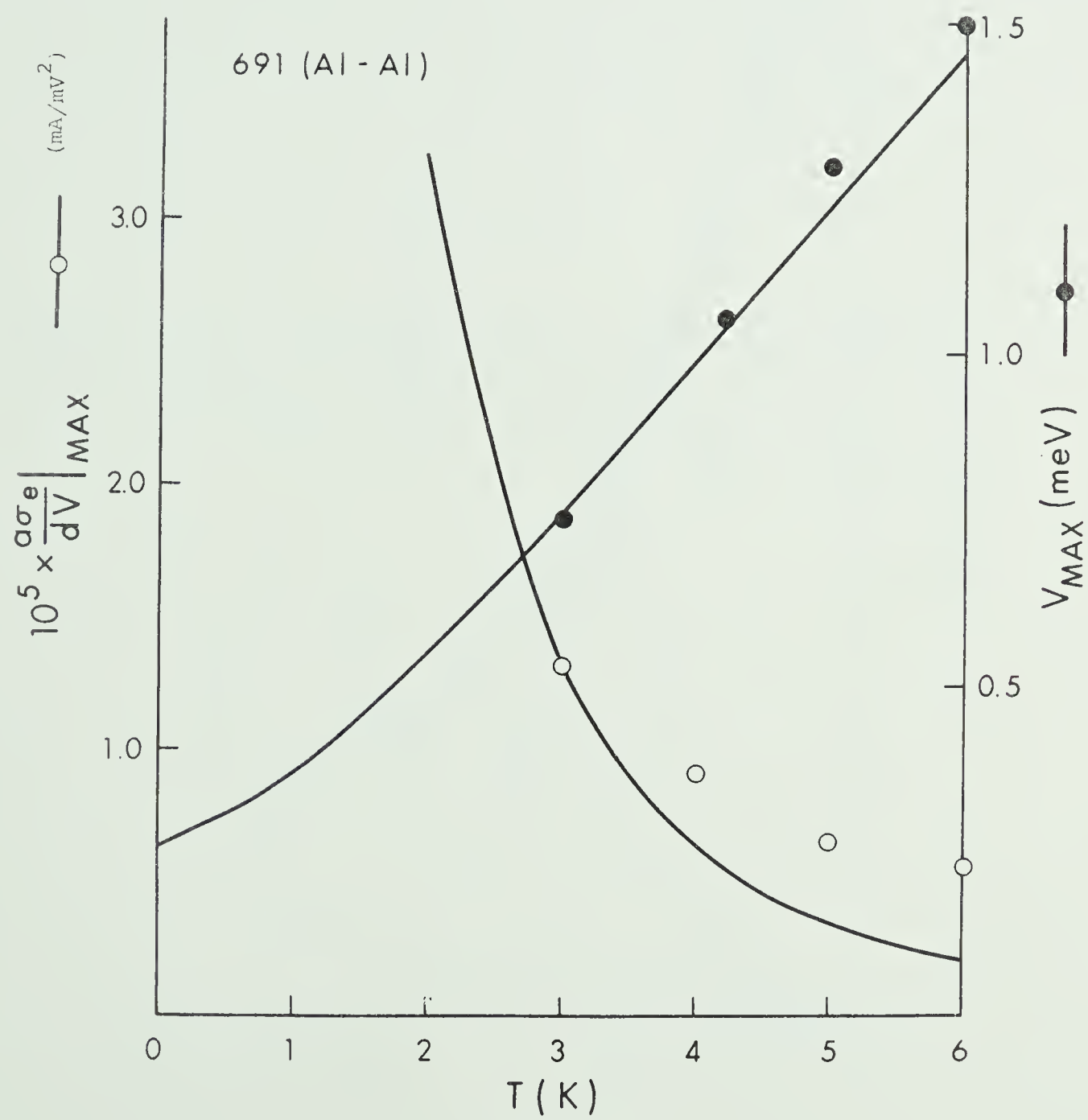




Fig. 4.17

$\frac{d\sigma_e}{dV}$ vs V for an Al/Al junction. Solid lines represent data; dashed lines theoretical result for $T = 3$ K.

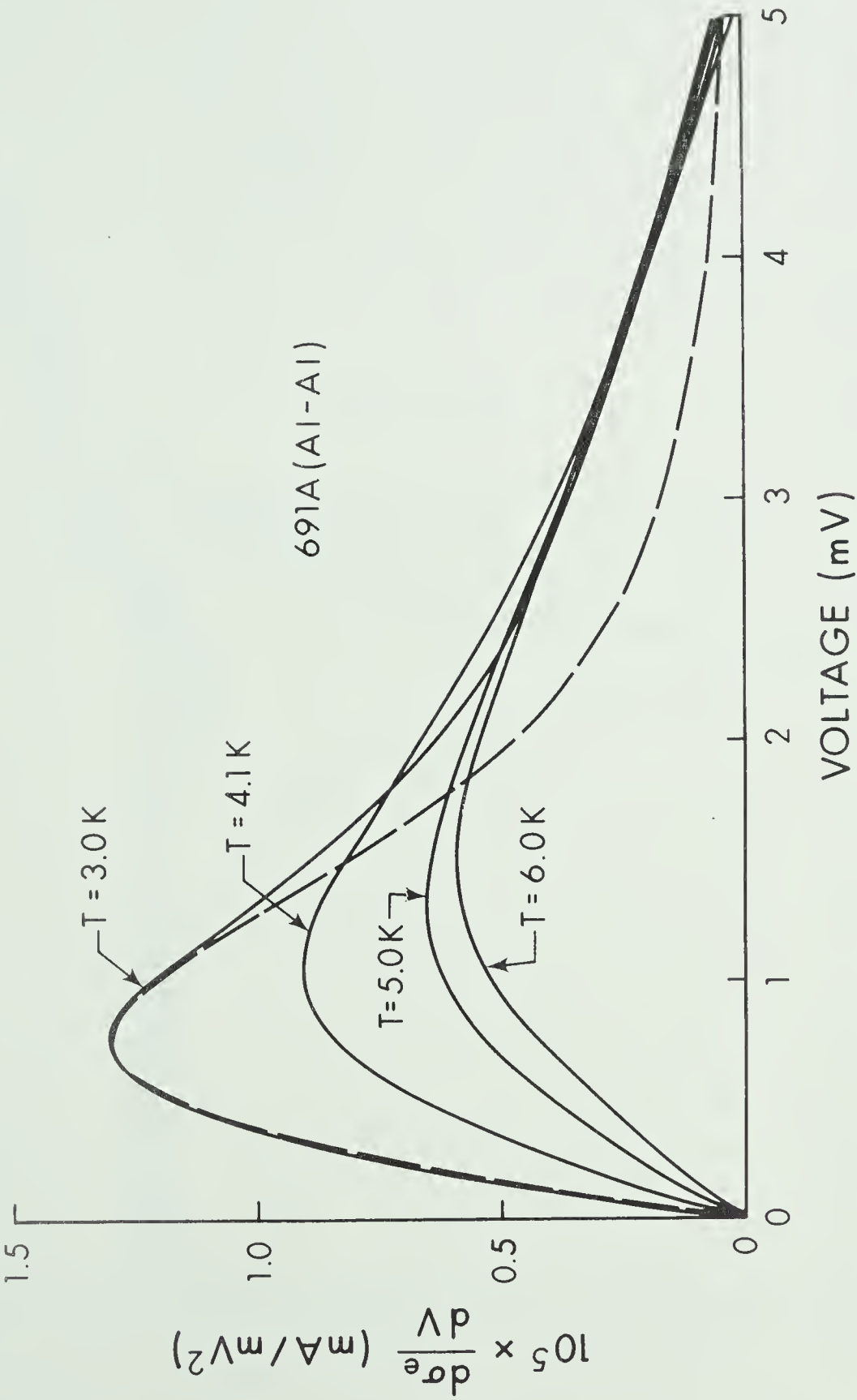




Fig. 4.18

Illustration of the appearance of the
superconducting energy (at 2 K) gap in
an Al/Al junction.

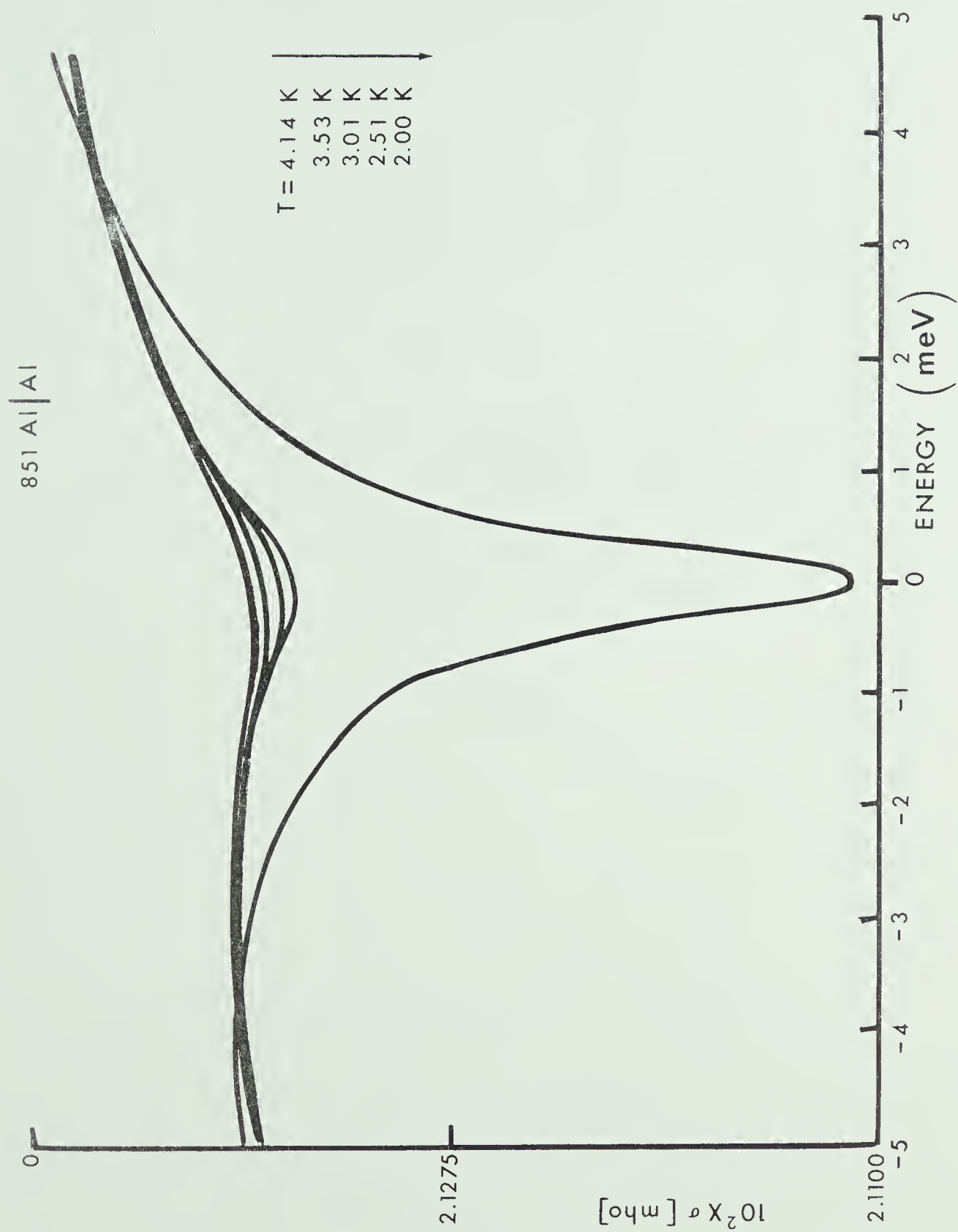
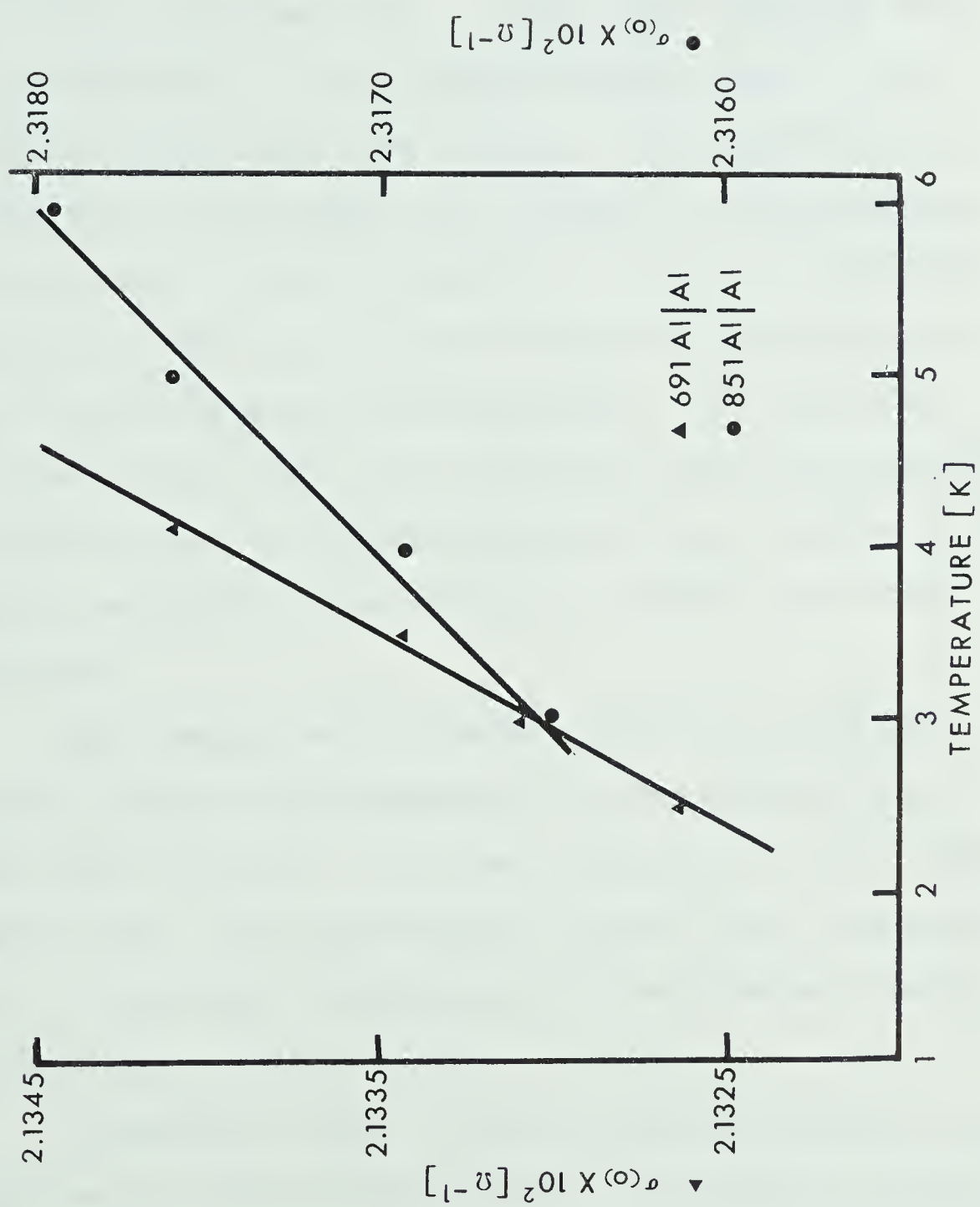




Fig. 4.19

Temperature dependence of the blocking conductance at zero bias for 691 Al/Al and 851 Al/Al. The solid lines are just indicating the linear behaviour.



4.5 Discussion

In the last section we have presented the results of the experimental investigations on small conductance decreases around zero bias. These were compared with the predictions of the transport model, based on the non-equilibrium tunneling theory. The temperature dependence of the anomaly was fitted by one parameter, the knowledge of which allowed to extract the impurity relaxation time, τ_i , if the strength of the electron-phonon coupling was known beforehand. The amplitude of the theoretical curve was adjusted to the experimental one with an aid of another parameter, τ_B , related to the barrier penetrability coefficient and the electrode thickness.

The theory, as it stands, predicts a somewhat stronger temperature dependence of the observed peak amplitudes in $d\sigma_e/dV$. The peak positions, at the lowest temperatures, lie approximately 10-20% below the predicted curve. A possible explanation of the observed discrepancies will be given below.

A magnetic field oriented perpendicularly to the direction of the tunneling current reduced the conductance anomaly. This effect was explained on the basis of the Lorentz force induced drift of the electrons with which we associated a relaxation time proportional

to the strength of the applied field. No observable changes in the anomaly were observed if the magnetic field was applied parallel to the direction of the current flow.

The behaviour of the conductance with the magnetic field is instrumental in eliminating the structure around zero bias as being due to paramagnetic impurities. It is well known that these can produce either large conductance reductions of the order of 100% and 100 meV wide (Rowell, Shen, 1966) or conductance peaks (Wyatt, 1964) depending on the amount of the deposit and its position with respect to the barrier (Lythall, Wyatt, 1968; El-Semary, Rogers, 1972; Appelbaum, Brinkman, 1970).

Junctions with low impurity concentrations produce conductance peaks which are temperature and magnetic field dependent (Shen, Rowell, 1968; Lythall, Wyatt, 1968). The size of the anomaly is usually of the order of 10%, being a few meV wide. With the application of the magnetic field, the conductance peak first decreases and with higher fields splits into two peaks, the separation of which is proportional to the field. These results have been explained (Anderson, 1966; Appelbaum, 1966, 1967) by considering the interaction between the tunneling electrons and the magnetic impurities. Increasing the amount of the deposit leads to a large conductance

The first part of the paper discusses the importance of the
 research and the objectives of the study. It also outlines the
 methodology used in the study and the data sources. The second
 part of the paper presents the results of the study and discusses
 the implications of the findings. The third part of the paper
 concludes the study and provides recommendations for future
 research. The paper is organized as follows: Introduction, Literature
 Review, Methodology, Results, Discussion, and Conclusion.

reduction which, however, is magnetic field independent (Rowell, Shen, 1968). It is now believed (Wolf, 1974) that this effect is more likely connected with the Giaver-Zeller (Zeller, Giaver, 1969) tunneling, rather than being a manifestation of the interaction between the tunneling electrons and the interacting magnetic impurities (Gupta, Upadhyaya, 1971). The dominant current flow in Giaver-Zeller tunneling is through a two step tunneling process in which an electron first tunnels onto the particle embedded inside the barrier and subsequently tunnels into the second electrode. Since the localization of the electron on the impurity requires an activation energy, this process leads to a strongly non ohmic behaviour. At finite temperatures the zero bias conductivity, $\sigma(0,T)$ is proportional to the number of thermally excited electrons residing on the particle. This is given by

$$\sigma(0,T) \sim \int_0^{\infty} e^{-E/k_B T} \sim T \quad (4.10)$$

where E is the activation energy of the excitation.

At this point we call attention to fig. 2.6, where we notice that the zero bias blocking conductance within a certain temperature limit (depending on Γ) is a linear function of the temperature. Thus the behaviour

of the small conductance decreases at zero bias which is linear with temperature can be misleading in believing that the tunneling is through particles (Josefowicz, Smith, 1973). A comparison between the observed magnitudes of the corresponding anomalies ($\sim 100\%$ for the two step tunneling vs. $< 1\%$ for the non-equilibrium effect) and their magnetic field dependence helps to resolve this ambiguity.

Let us turn our attention to the possible sources of observed differences between the theory and the experiment. One of these arises from the fact that the energy and temperature dependent electron-phonon relaxation time was assumed to be momentum independent. There are several sources of anisotropy. The most obvious is the deviation of the Fermi surface sphere. Another results from the anisotropy in the electron-phonon interaction and in the phonon spectrum. Recent calculations (Carbotte, Truant, 1974) have shown that this anisotropy affects strongly the value of the electron-phonon relaxation time. Large variations over the Fermi surface were found even at $T = 30$ K. For aluminum the ratio of $\tau_{ep}(\theta, \phi, T) / \tau_{ep}(0, 0, T)$ can be as high as 10 ($\vec{k} \equiv (k_F, \theta, \phi)$). The anisotropy in the electron-phonon relaxation time suggests a further set of experiments in which the electrons would tunnel into single

crystal electrodes having a definite crystallographic orientation. We would expect a certain degree of correlation between the size of the zero bias anomaly and the orientation of the crystal with respect to the incoming electrons.

A more transparent source of a discrepancy arises because of the assumption that phonons created by the relaxing electrons are in equilibrium with the thermally excited phonon gas. The thermalization of the excess phonons was assumed to be immediate with the aid of a perfect heat bath. Thus their further role in the deblocking process has already been described by the previously considered electron-phonon scattering process, leading to a relaxation time given by eq. (2.10). Such a simplification is not always valid. If the lifetimes of the emitted phonons were "long enough" an incoming electron could absorb one of these and thus be scattered into a higher energy level. This results in a removal of the electron from the forward direction, thereby deblocking the occupied state. The process is in sharp contrast with the deblocking considered by the theory previously and being only due to the interaction between the tunneling electrons and thermal phonons.

It is illustrative to consider the order of magnitudes involved in order to obtain an estimate

whether an additional deblocking due to non-equilibrium phonon absorption is possible. The rate of thermalization through the surrounding bath can be characterized by

$$\tau_{\text{bath}} = \frac{L}{v_s} \quad (4.11)$$

where L is the film thickness and v_s is the sound velocity in the metal. For a $1000 \text{ \AA}$ film, and $v_s = 5 \times 10^5 \text{ cm/sec}$, $\tau_{\text{bath}} = 2 \times 10^{-11} \text{ sec}$. The relaxation time of phonons due to their absorption by electrons at $T = 0 \text{ K}$ is given by equation (4.12) (Truett, et al, 1969)

$$\frac{1}{\tau_{\text{ph-e}}} = \frac{2}{9} \frac{E_f^2}{\pi \rho_o v_s} \left(\frac{m}{\hbar}\right)^2 \epsilon \quad (4.12)$$

where ρ_o represents the density of the metal. At 1 meV and $\rho_o = 10 \text{ g/cm}^3$, $E_f = 10 \text{ eV}$, $v_s = 5 \times 10^5 \text{ cm/sec}$

$$\tau_{\text{ph-e}} = 2 \times 10^{-10} \text{ sec}.$$

This is comparable to τ_{bath} and the relaxation time of electrons due to their interaction with the equilibrium phonon gas. It follows that electrons can be

additionally deblocked by scattering with the non-equilibrium phonon gas. Thus in steady state we should solve a coupled system of Boltzmann transport equations relating the non-equilibrium situation in the phonon and electron gas.

$$\frac{\partial N}{\partial t} = 0 = \left(\frac{\partial N}{\partial t}\right)_{\text{scatt}} + \left(\frac{\partial N}{\partial t}\right)_{\text{ph-e}} \quad (4.13)$$

$$0 = \left(\frac{\partial f}{\partial t}\right) = 0 = \left(\frac{\partial f}{\partial t}\right)_{\text{tunneling}} + \left(\frac{\partial f}{\partial t}\right)_{\text{e-ph}} + \left(\frac{\partial f}{\partial t}\right)_{\text{scatt}} \quad (4.14)$$

The interpretation of different terms in eqs. (4.13) and (4.14) is obvious.

The solution of the coupled equations is beyond the scope of the present work. Instead of this, let us see what possible results can one deduce on the basis of the previous considerations. First of all we can crudely estimate the importance of the additional deblocking mechanism. Let us assume that the effective relaxation time of electrons due to their interaction with phonons can be written as

$$\frac{1}{\tau} \sim \frac{1}{\tau_{N_0}} + \frac{1}{\tau_{\delta N}} \quad (4.15)$$

where $N = N_0 + \delta N$. $\tau_{N_0} = \tau_{\text{ep}}$ - gives the part of the lifetime relaxation which is associated with the equilibrium phonon distribution (eq. 2.10). Setting

$\tau_{\delta N} = \tau_{\text{ph-e}}$ (eq. 4.12) we further assume that the non-equilibrium phonons relax only by a scattering with the transmitted electrons. The amount of relaxation due to

excess of phonons is negligible only if $\tau_{\delta N} \gg \tau_{N_0}$. At $T = 0$ K, recalling eqs. (2.12), (4.12), this is satisfied

for

$$\varepsilon \gg \frac{\hbar}{\pi a} \cdot \frac{E_f^2 m^2}{2\pi\rho_0 v_s \hbar^4} \quad (4.16)$$

$$\varepsilon \gg .3 \text{ meV}$$

for the typically used quantities. Practically then at ~ 3 meV, the contribution of non-equilibrium phonons to deblocking is minimal.

Secondly at $T = 0$ K we expect that the size of the conductance dip at zero bias is unaffected by the incorporation of the non-equilibrium phonons into the theory. This follows from the fact that at zero bias there are no non-equilibrium phonons created since the tunneling current is zero. As voltage is imposed across the junction the zero bias anomaly decreases sharper because of the additional deblocking mechanism previously neglected by the theory. This leads to a shift of $V_{\max}$, the peak position in $d\sigma_e/dV$, to a lower bias with a simultaneous increase in the peak amplitude. With increasing temperatures, the influence of the non-equilibrium phonons is minimized by a greater thermal phonon population.

All these results point to correction factors which when included in the theory could explain the observed experimental discrepancies. Since the nature of this discussion is purely qualitative, it is impossible to present exact values of these.

CHAPTER 5

RESONANT ELECTRON TUNNELING

5.1 Introduction

The measurements of zero bias anomalies on some junctions of Mg/oxide/Mg, Mg/oxide/Au and Mg/nitride/Au have produced characteristics which had marked differences from those shown in the previous chapter.

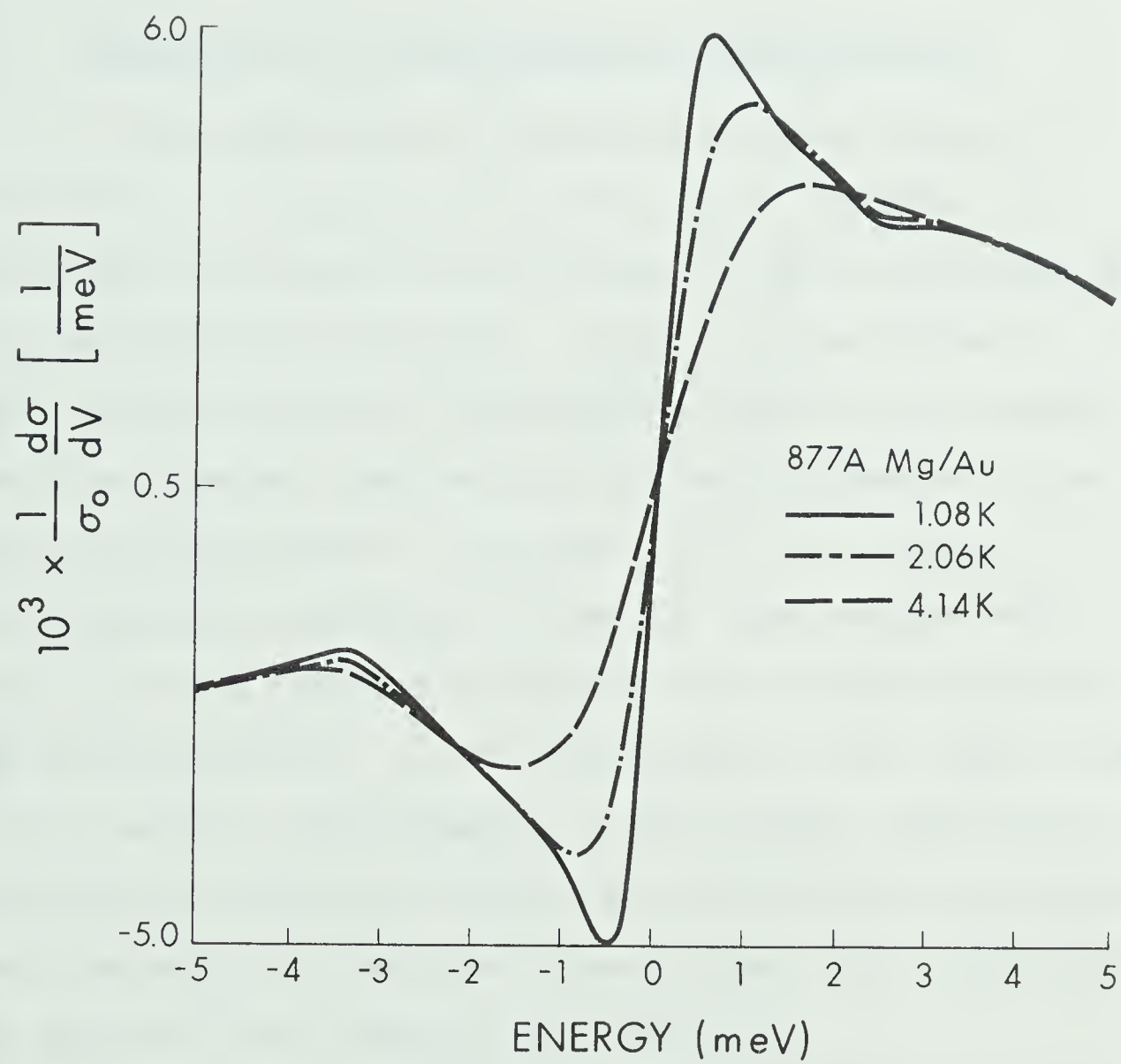
As a representative of junctions of this unusual behaviour we show a temperature dependence of $\frac{1}{\sigma_0} \frac{d\sigma}{dV}$ for junction 877A (fig.5.1). Note the usual set of peaks close to zero bias reflecting the discussed blocking effect with very weak additional structures seen at -3.5 meV and +1.8 meV. The structure as compared to the background is less than 5%, with the background itself being of the order $\sim 5 \times 10^{-3} \text{ meV}^{-1}$. The order of magnitudes involved in observation of such effects again documents the necessity of measurements at lowest attainable temperatures and modulations to avoid thermal and instrumental smearing. The calculated relaxation times for the junction 877A agree well with the relaxation times for samples without the additional structures.

The set of unexpected peaks in $\frac{1}{\sigma_0} \frac{d\sigma}{dV}$ prompted an investigation as to their physical origin and resulted



Fig. 5.1

Illustration of a junction having weak additional structure in the derivative of the conductance.





in the present chapter. To substantiate our possible explanation of the observed effect we find it appropriate to present first the results of the experiments on junctions showing the new oscillatory structure.

5.2 Experimental investigations of oscillations

The occurrence of the new structure was not restricted to junctions of Mg/Au type. In fact, we have observed the additional peaks in $\frac{d\sigma}{dV}$ in Mg/oxide/Mg and Mg/oxide/Pb junctions. In fig. 5.2 we present a $\frac{d\sigma}{dV}$ characteristics for Mg/oxide/Mg junction with peaks which are better resolved and are more numerous in the same voltage range as compared to fig. 5.1. The corresponding conductance curve is shown on the next fig. 5.3 with noticeable changes in its shape close to $\frac{d\sigma}{dV}$ peak positions. It is interesting to note that in one of our earlier measurements on Mg/oxide/Pb junctions we have seen a structure similar to the presently investigated one which at the time of measurement were considered to be due to the noise in the junction.

The appearance of a structure in Mg/Au and Mg/Pb junctions gave rise to a suspicion that it is connected either with the Mg electrode or with its insulating oxide. In view of this fact, we have decided to investigate the

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Fig. 5.2

Conductance vs energy for a Mg/Mg
junction having oscillations.

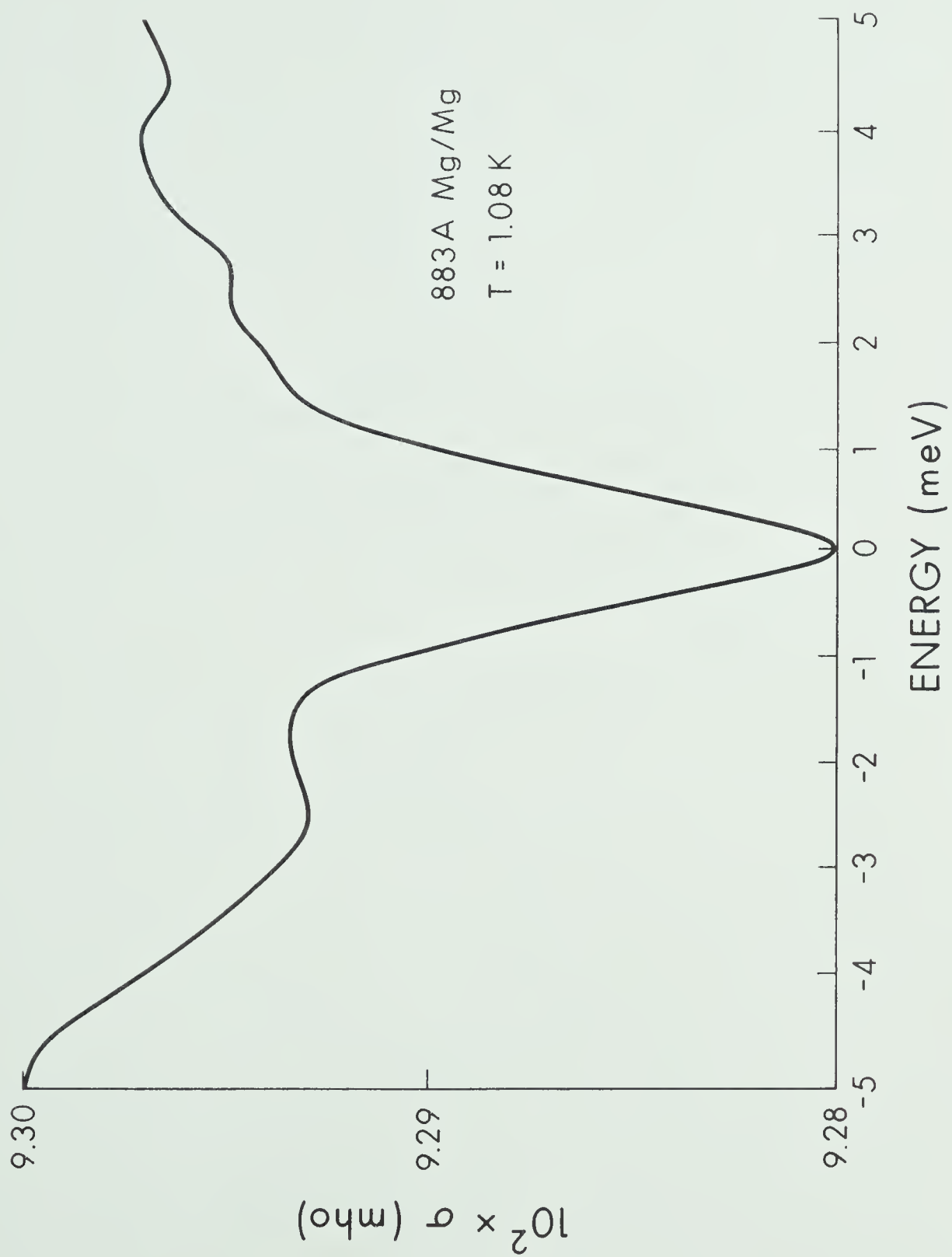
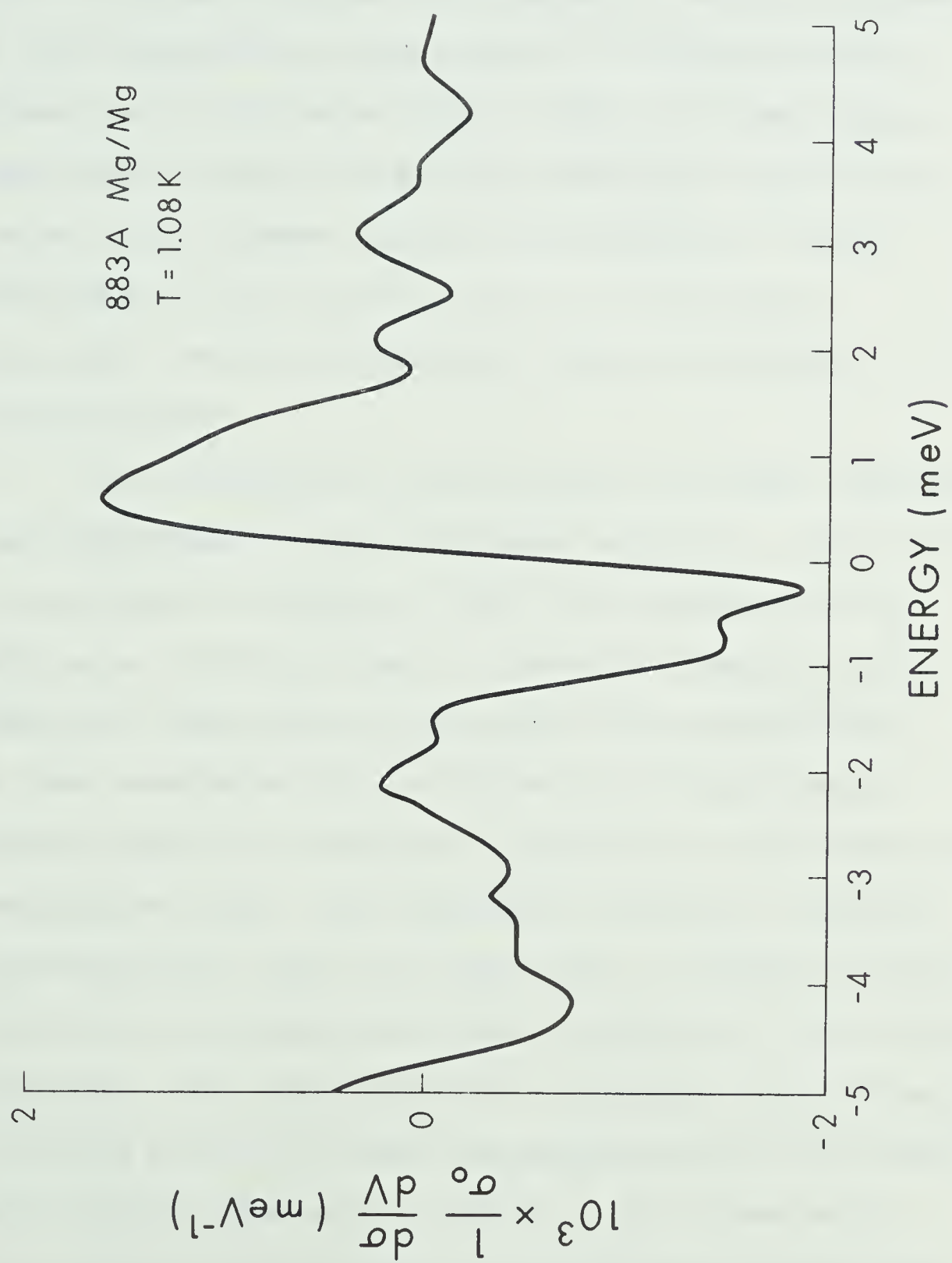


Fig. 5.3

Derivative of the conductance for
a Mg/Mg having oscillations



new effect on Mg/Au junctions since the likelihood of their successful preparation proved to be the greatest. We have accepted the observation of phonon emission either in Mg electrode (Adler, 1969) or in MgO (when applicable) (Adler, 1969) as a sufficient proof that the measured current was due to tunneling. Since the peaks in $d\sigma/dV$ tend to have an oscillatory character, we shall henceforth refer to them as "oscillations".

The existence of oscillations in tunnel junctions was independent of the techniques of sample preparation as described in Chapter 3, and the occurrence of the additional structure even in junctions prepared under identical experimental conditions was unpredictable. We have considered the thickness of the electrodes, junction area, the chemical composition of the barriers, evaporation rates, glow discharge currents, oxidation (nitridation) times and pressures as variables which could have influenced the final properties of the tunnel junctions. The magnesium film thickness ranged between 700-30000 Å with the gold counterelectrode of 600-3000 Å and junction areas of .01-.05 mm². The evaporation rates varied from 10 Å/sec to 1000 Å/sec at pressures of 2×10^{-6} atm. The combined effects of the glow discharge current, oxidation (nitridation) time and pressure are

reflected on the tunnel junction resistance which in our samples ranged between 15-8000 Ω at He⁴ temperatures. The decision to make junctions with nitride barriers was taken with a hope of altering the barrier composition and thus possibly changing the physical properties of the metal-barrier interface which we thought to be responsible for the appearance of the oscillations.

In fig. 5.4 to fig. 5.12 we present some typical characteristics we have obtained while measuring the properties of Mg/Au junctions having magnesium oxide or nitride as their insulating barriers.

To illustrate the effect of the temperature smearing, we show $\frac{1}{\sigma_0} \frac{d\sigma}{dV}$ measured at 1 K and 4 K for a junction with weak oscillations (fig. 5.4). First we notice a decrease in the blocking effect due to the elevated temperature with a continuous smearing of the resolved peaks (at 1 K) into the smooth and wide background curve at 4 K. The slight overshooting of the 1 K curve at -5 meV with respect to the background is due to the oscillatory peak at -3.6 meV. The total variation of the conductivity between 0 - 5 meV at 1 K, represents only 4 parts in 10^5 .

The most drastic oscillatory behaviour was observed in 875B Mg/oxide/Au. The 4 K curve (fig. 5.5)



Fig. 5.4

Illustration of the effect of the temperature
on the size of the oscillations in $\frac{1}{\sigma_0} \frac{d\sigma}{dV}$.

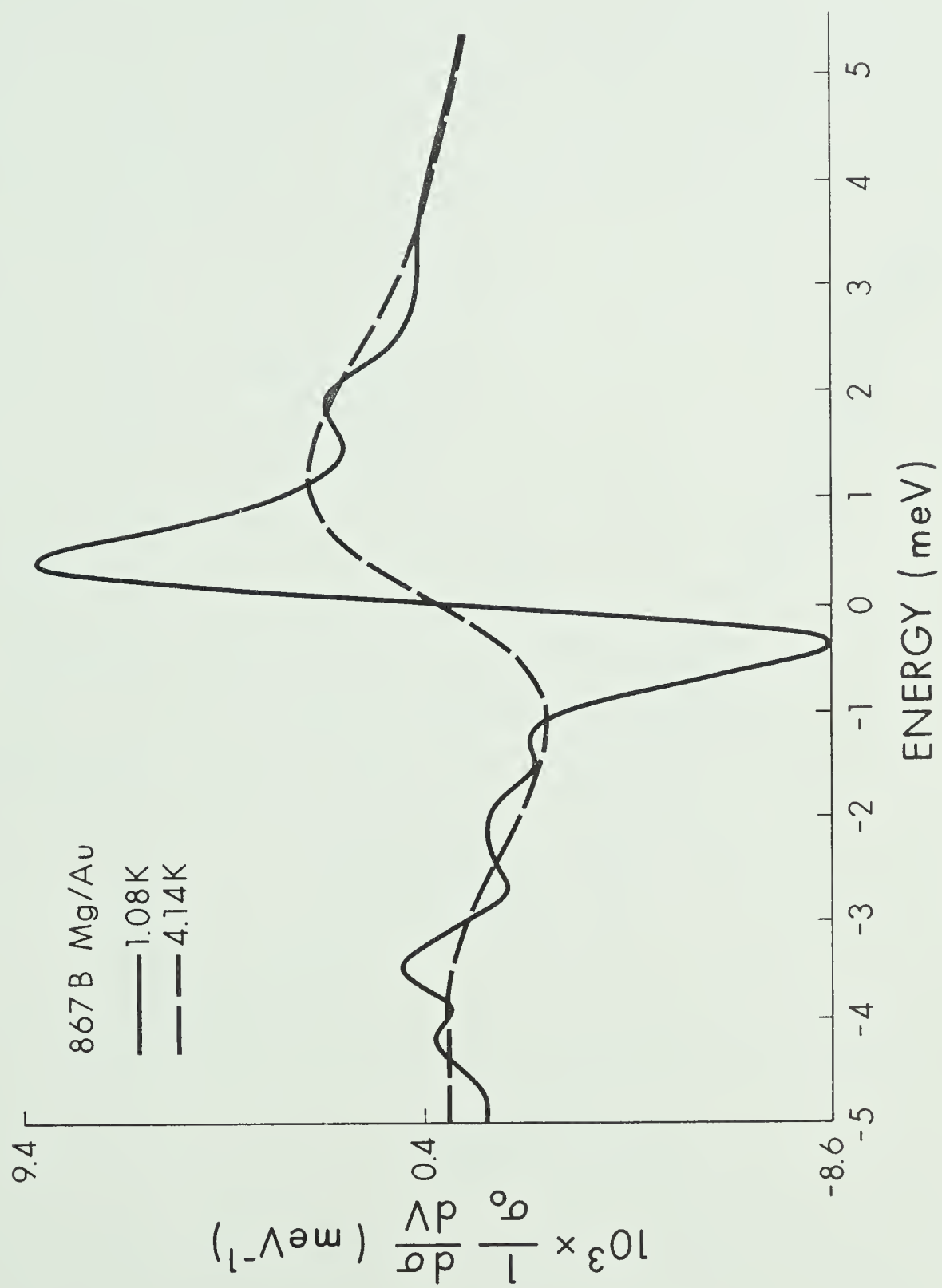




Fig. 5.5

Illustration of a junction having well resolved oscillatory peaks in the conductance. The effect of the temperature smearing is shown as well.

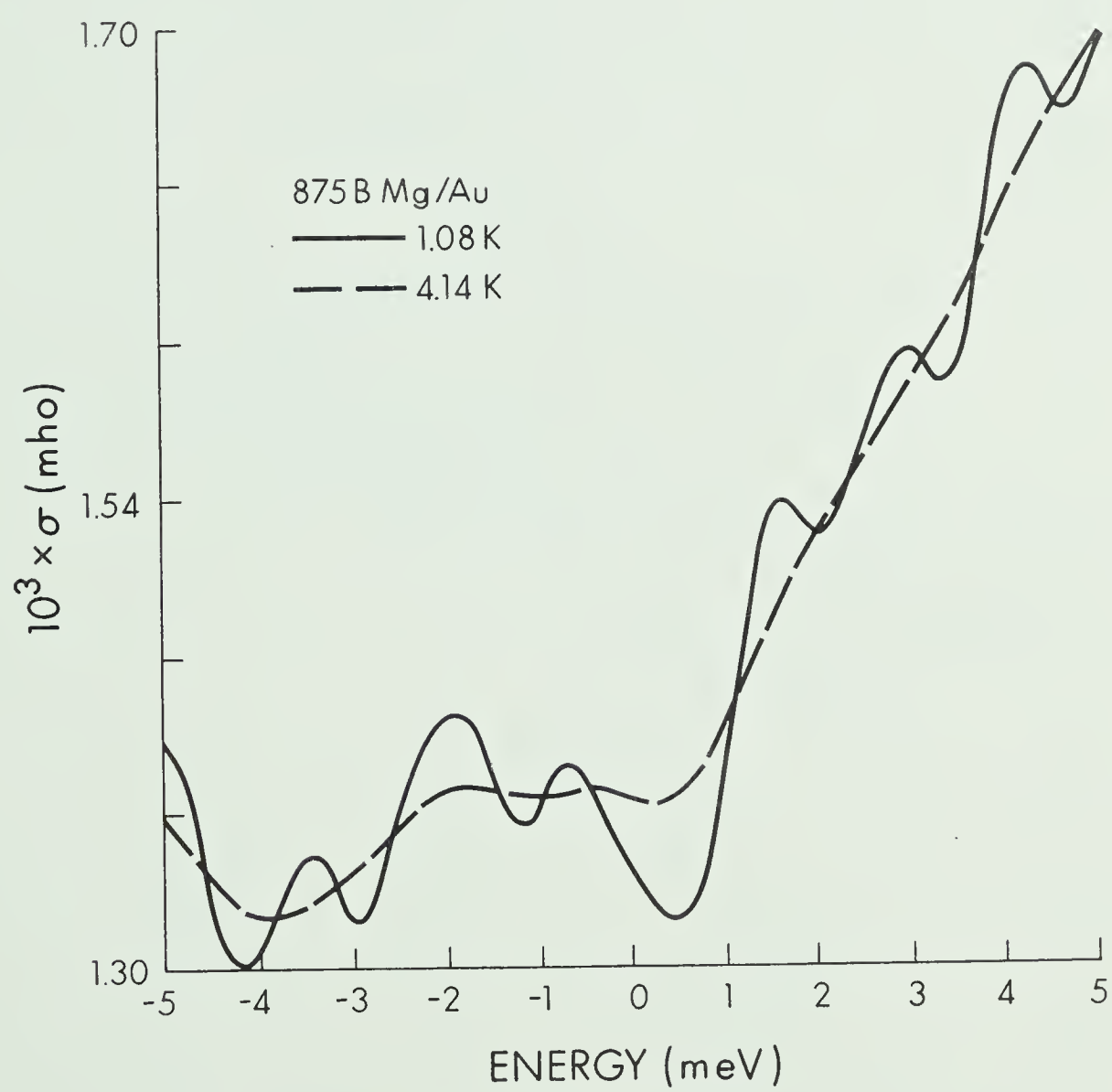
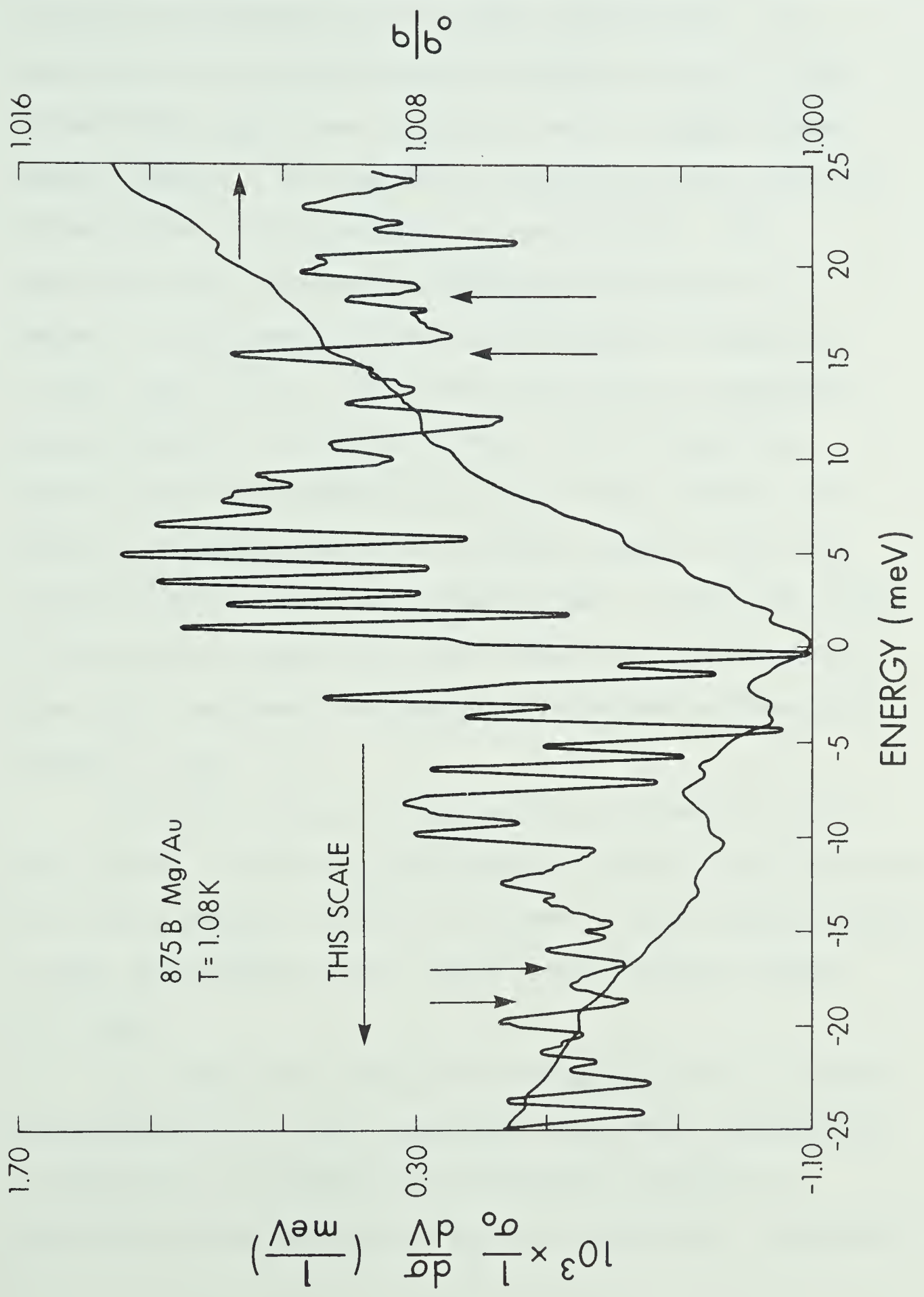




Fig. 5.6

The conductance resp. derivative of the conductance vs energy for 875B Mg/Au measured to ± 25 meV. The arrows indicate the expected phonon emission threshold.



again passes smoothly through the oscillations which are strongly pronounced at the lowest temperature. In contrast to the previously seen kinks in fig. 5.3 the conductivity curve now displays a set of humps almost equally spaced. The asymmetric offset at zero bias is probably due to the oscillatory background. The regularly well resolved oscillations persisted to almost ± 10 meV beyond which they started to diminish in size (fig. 5.6). The arrows indicate the expected phonon emission threshold in Mg. For the positive applied bias the conductivity curve has a series of steplike increases which are almost smeared into the structureless background beyond 10 meV. Since the slope of the curve is smaller on the negative side the structure still retained its humplike behaviour as seen previously in fig. 5.3.

Finally, for an illustration we present a junction having a nitride as its barrier showing oscillations in ± 25 meV region. The 4.2 K curve is again superimposed to show the effect of the temperature smearing (figs. 5.7, 5.8).

An important result which contributed to a possible explanation of the tunneling curves was obtained by an adsorption of hydrocarbon molecules inside the insulating layer during the barrier formation. Junctions



Fig. 5.7

Illustration of the oscillations in a Mg/N₂/Au junction measured to ± 25 meV. The arrows indicate the expected phonon emission threshold.

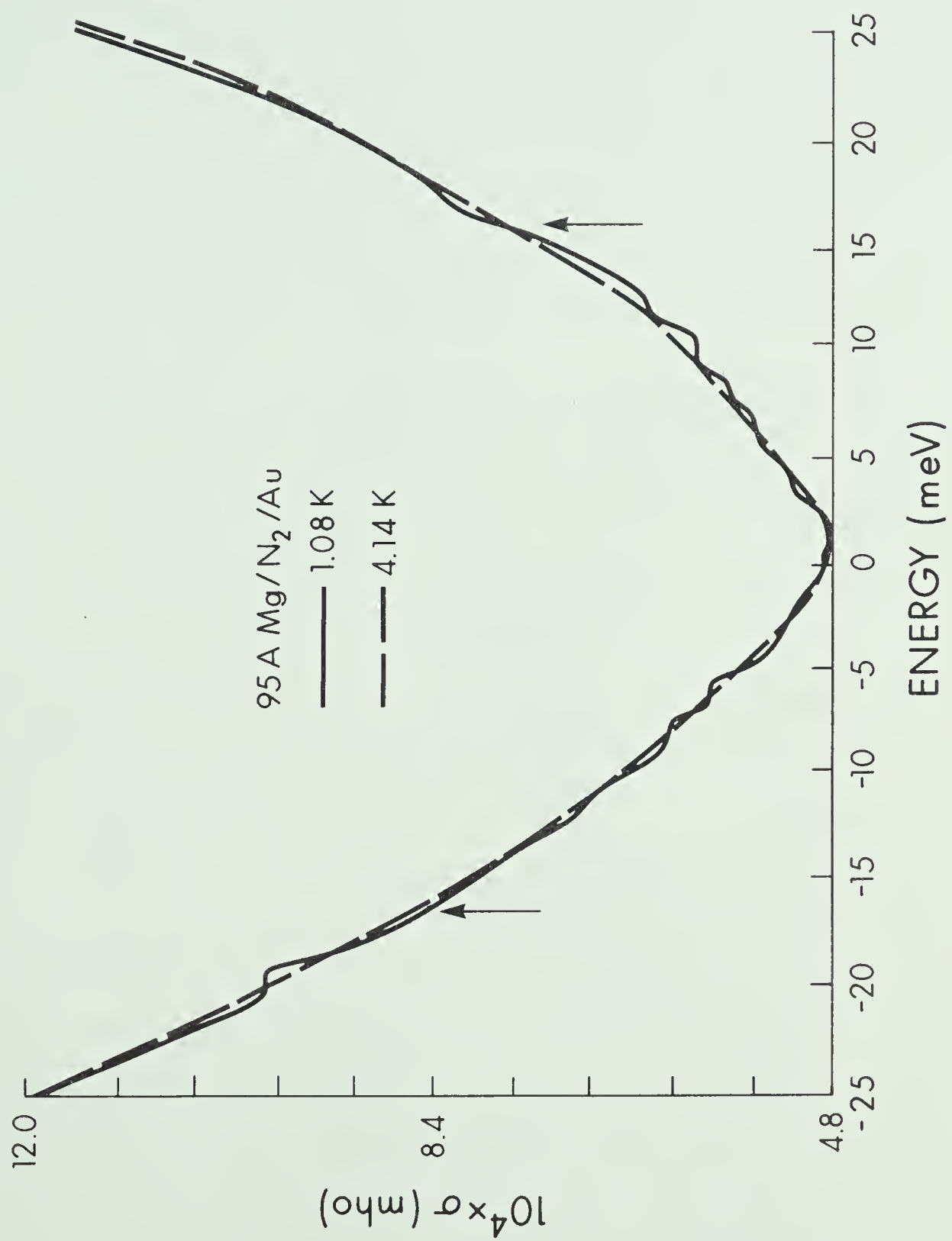
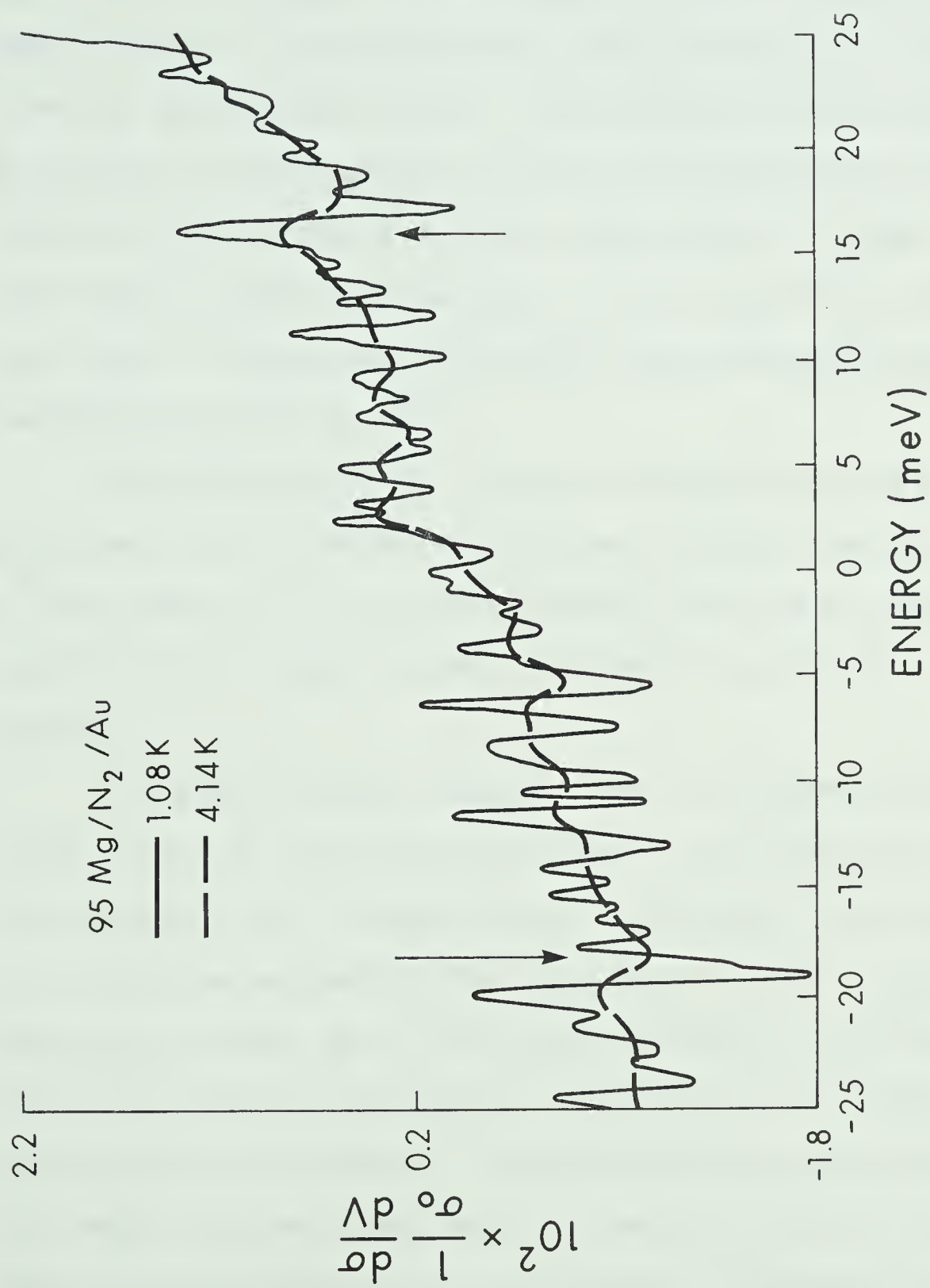




Fig. 5.8

Derivative of the conductance vs energy
for a Mg/N₂/Au junction.



so prepared were subjected to oil vapours during oxidation (nitrication) by passing the oxygen (nitrogen) gas through a flask containing light machine oil heated close to its boiling point. The presence of adsorbed molecules of hydrocarbons inside the barrier drastically affected the tunneling barrier with respect to the occurrence of the oscillations. In all junctions of this type no additional structure superimposed on the background curve was seen.

The verification of the oil adsorption was performed by an observation of the inelastic spectrum of the junction at bias range where previously reported (Jacklevic and Lambe, 1968) hydrocarbon peaks were located.

To gain further insight into the nature of the oscillations we have tried to alter the properties of the junctions by an application of external perturbations such as annealing the junctions to room temperatures, applying voltages up to 1000 meV across the junctions and polarizing the interface by passing DC currents along its adjoining electrode. We hoped that by correlating the newly obtained results with characteristics measured before the application of the external influences we could extract additional information which would help to interpret our data. Such an effort proved to be quite fruitful as it will be seen on the following figures.

Junction 080B when measured after an initial cooldown to 1 K had oscillations in its characteristics. These, however, disappeared upon annealing the junction to room temperature while still keeping it in a vacuum (figs. 5.9-5.10). The annealing produced a 36% decrease in junction resistance, while the change in resistance over the spanned voltage region approximately remained the same (1.93% and 2.02%). The sharper conductivity increase around zero bias reflects the tail of the first smeared oscillation. In contrast to this result, an application of 700 meV (Mg positive) across another junction for 1 hour produced a stronger structure which in the earlier measurement was weakly visible (fig. 5.11). Besides the better resolved structure, there is a slight shift in peak positions (fig. 5.12). The relative change of the conductance at zero bias $(\sigma_{4.2}(0) - \sigma_{1.1}(0))/\sigma_{1.1}(0) = 0.0145$ due to zero bias anomaly in both cases remained the same implying that the boundary and impurity scattering mechanisms which helped to deblock the tunneling electrons in the metal electrodes were not altered. Thus only a change in electron transition rate $1/\tau_B$ is responsible for the change in the junction resistance (from 210.97Ω to 201.86 at 1 K).

Similar results were obtained by passing a DC current along the bottom (Mg) or top (Au) electrode.



Fig. 5.9

Comparison of the conductance curves for
080B Mg/Au before and after annealing.

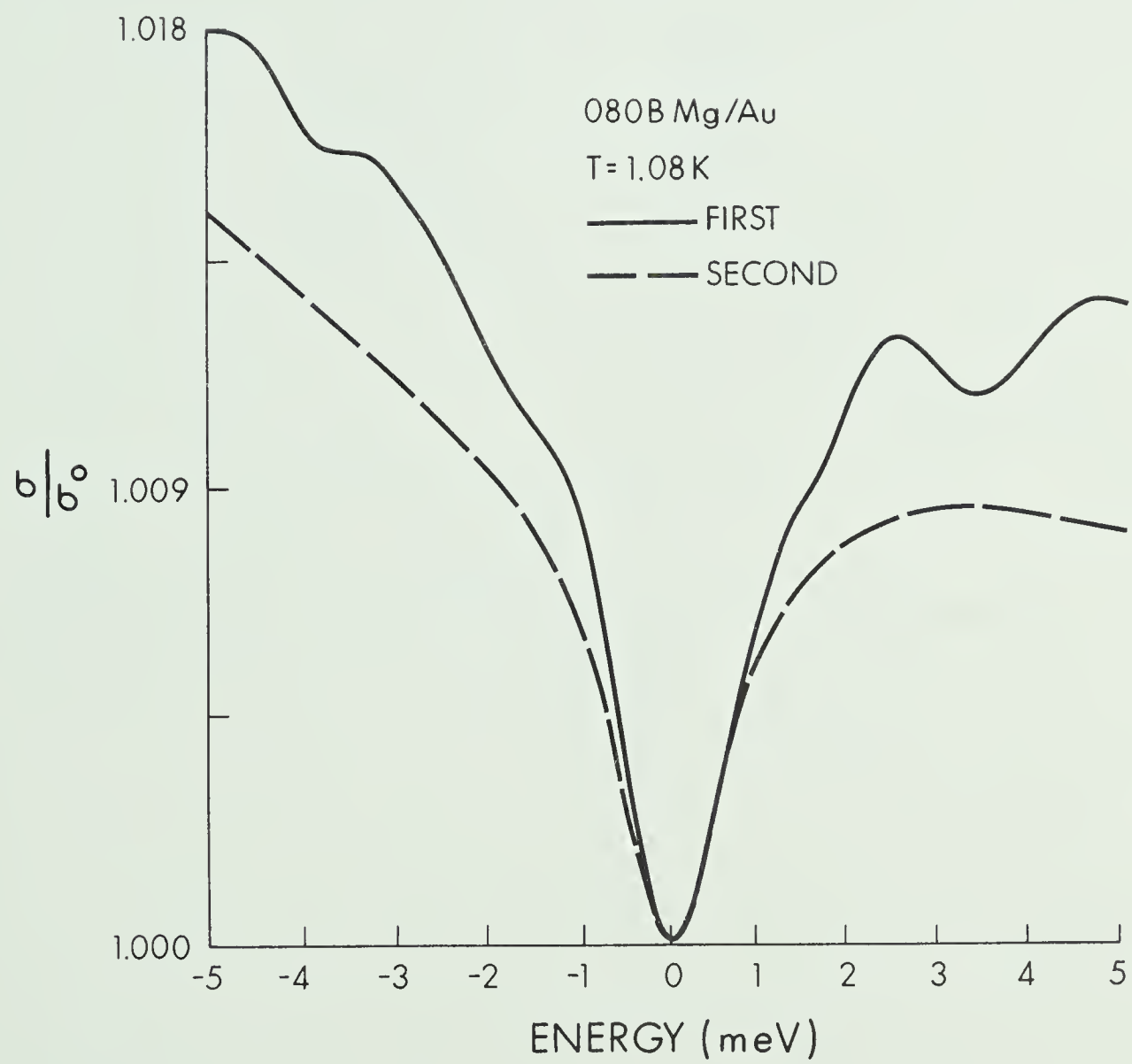




Fig. 5.10

Comparison of the derivative of conductance curves for 080B Mg/Au before and after annealing.

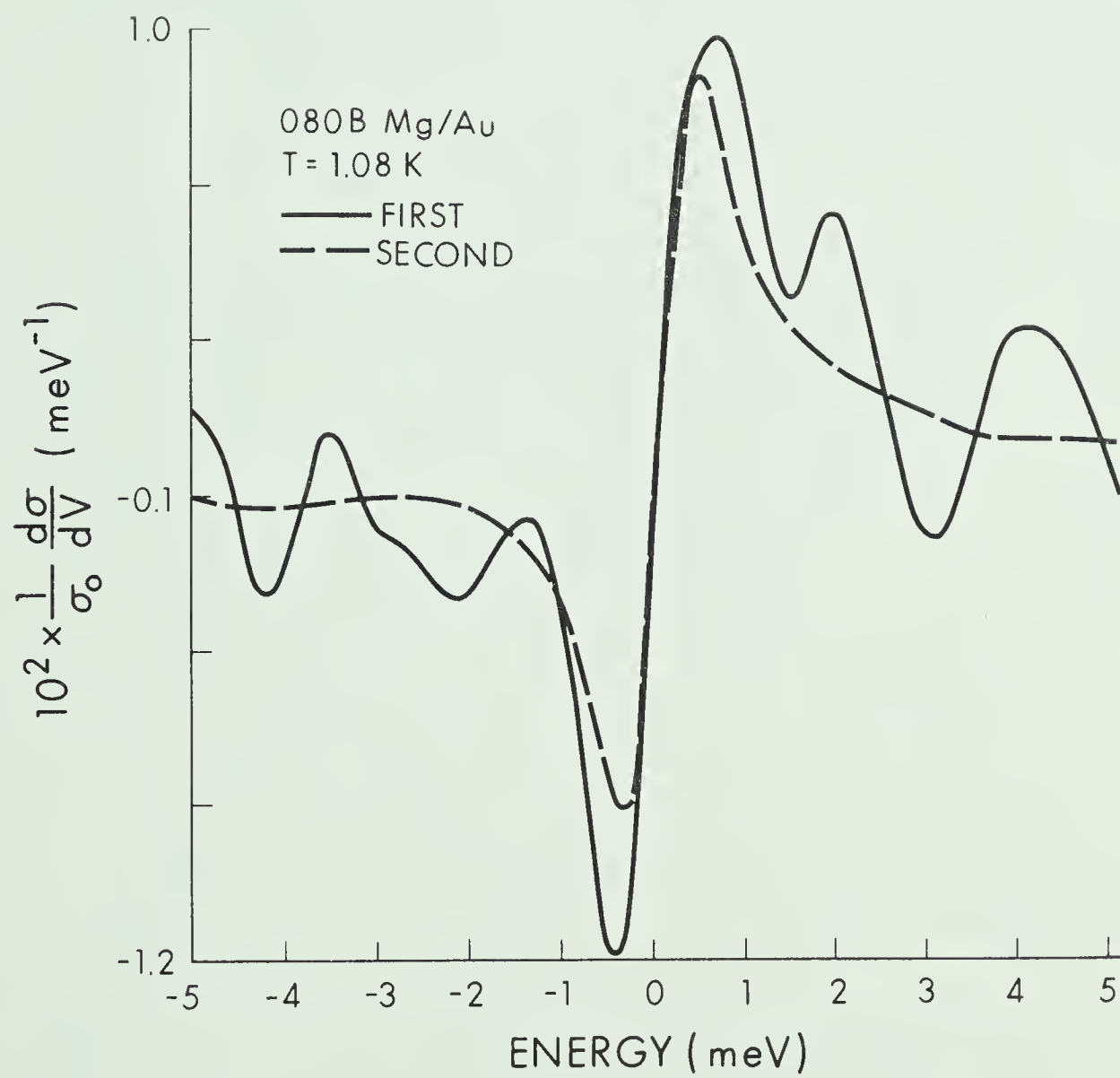


Fig. 5.11

Comparison of the conductance curves for
J107B Mg/N₂/Au before and after applying
high bias across the junction.

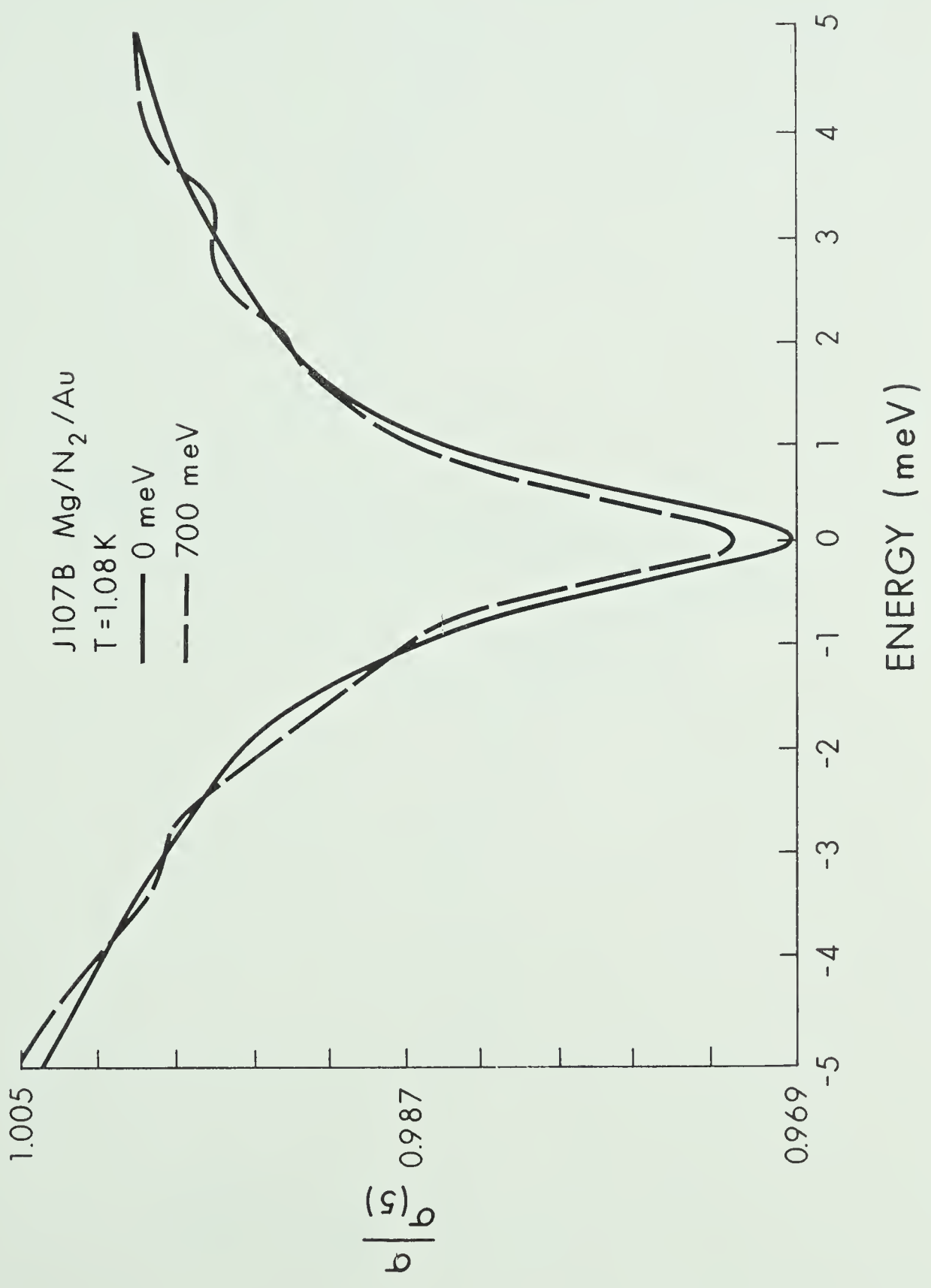
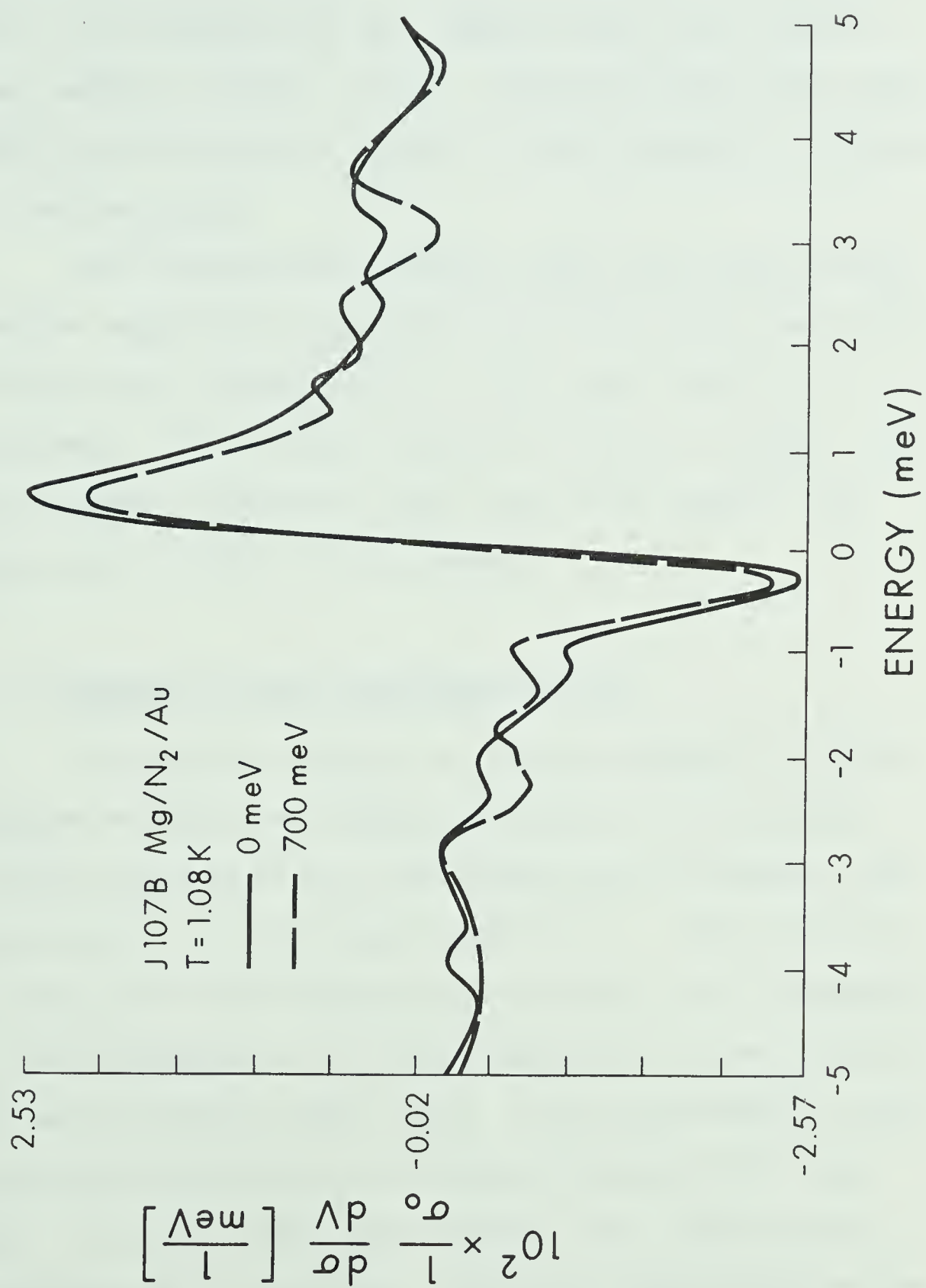




Fig. 5.12

Comparison of the derivative of the conductance curves for J107B Mg/N₂/Au before and after applying high bias across the junction.



With increasing currents the resistance of the junctions continuously increased. We interpret this as being due to the burning of thin edges across the junction area (Adler, Kreuzer, 1972). Simultaneously with this effect we have seen a change in the oscillation pattern of the junctions.

The information revealed from the above quoted results represents the main line along which the analysis and the interpretation of the data will be performed. In the next section we shall consider this and suggest a physical model which can explain the appearance of the new structure.

5.3 Analysis of the experimental data

Through the results of the experimental investigations on Mg/Au and Mg/Mg junctions a new electron transfer mechanism was established which enhanced the conductivity of the tunnel junctions. The existence of the associated structure was found to be independent of the thickness of the electrodes and of the barrier. The most probable bias region of the occurrence of the structure was found to be within 25 meV of the zero bias. In some junctions, however, the oscillations persisted up to ± 100 meV. Since the amplitudes of the oscillations rapidly decreased with increasing temperatures the measurements had to be done at the lowest attainable temperatures.

The appearance of oscillations in $d\sigma/dV$ with an apparent periodicity of 0.8-2.7 meV led to an early speculation that the observed effect was due to resonances associated with the presence of the electron standing waves in Mg (Jacklevic et al, 1972). According to Jacklevic et al, the experimental observation of the box quantization requires a preparation of films with a very high purity and smoothness. This limited the thickness of Mg films in their experiments to 150 Å - 500 Å. To promote smoothness, the films had to be deposited onto substrates cooled to -100°C - 150°C, with a subsequent warmup to room temperature to achieve recrystallization. In contrast to this procedure our Mg films, 700 Å - 30000 Å thick, were evaporated onto substrates held at room temperature. We would then expect that the stringent conditions imposed on the observation of the standing waves were not reached. Furthermore, correlation between the thickness of the film and the peak separations in $d\sigma/dV$ has not been successful. For instance, film thicknesses of 25000 Å - 30000 Å are needed in order to resolve oscillations with a periodicity of ~ 1 meV. This thickness range is well above the thickness of the Mg film in junction 875 (700 Å), in which the oscillations were the most pronounced from all our samples. These considerations then point to a conclusion that the structure in our

junctions could not be connected with Jacklevic type resonances.

In order to gain further insight into the nature of oscillations, the tunnel junctions were subjected to the influence of external perturbations. As indicated in the last section, a thermal cycling, an application of high biases across the junction or a flow of a DC current along the electrodes produced irreversible changes in the junctions which resulted in the new tunneling characteristics. These could be repeatedly traced over, unless a new perturbation was reapplied. We have to mention, though, that the aging effects in thin films associated with the thermal cycling often led to a destruction of the tunnel junction. The same was true of the applied DC bias, resulting in the dielectric breakdown of the insulator. Nevertheless, we feel that the measurements performed on different samples revealed enough information for their mutual intercomparison.

We attribute the changes in the tunnel junctions as being due to modifications of the tunneling layer or of the interface. We further assume that the structure of the metal electrodes has not been altered. This is supported by an observation that the relative size of the conductance anomaly between 1 K and 4 K did not change, even though the oscillatory pattern in the

tunnel characteristics did so. The new tunneling curves may either reflect a change in the barrier profile arising from the additional growth of the insulating layer (Pollack, Morris, 1964) with a simultaneous change in the tunneling path or result from the spatial redistribution of impurities inside the barrier. Due to the exponential dependence of the transmission probability on the thickness and height of the barrier the first two effects merely alter the magnitude of the tunneling current which in turn determines the structureless background (Simmons, 1963; Stratton, 1962).

A considerable variation in the detailed behaviour of the junctions even for samples prepared under identical condition suggests that the structure is connected with the impurity content of the insulating layer. Clearly, the inelastic impurity assisted tunneling (Jacklevic, Lambe, 1968) associated with the vibronic excitation of the impurity has to be excluded. This follows since it is not expected that the inelastic conductivity enhancement threshold could be changed by annealing or by an applied DC bias (Geiger et al, 1969). The presence of an impurity inside the tunneling layer, however, often leads to a possibility of a resonant-two step tunneling process. This will happen if the impurity provides an attractive potential which may have a bound state within the barrier (Giaver-Zeller,

1968; Parker, Mead, 1969; Gadzuk, 1970; Duke, 1972). Then under favourable conditions a new tunneling channel can open up, in which the tunneling electron goes from the metal to the adsorbed impurity where it is partially localized and then tunnels through the reduced barrier into the second electrode. The degree of electron localization is very important in distinguishing between two possible processes. An impurity state with a deep and narrow attractive potential can lead to a capture of the tunneling electron with a characteristic lifetime longer than the barrier tunneling time.

A subsequent decay of the bound state with the transmission of the electron into the second electrode is essentially equivalent to Giaver-Zeller tunneling. A uniform distribution of bound state energies then leads to a large temperature dependent resistance peak. In contrast, the effect on the impurity potential on the tunneling electron can be such that it will allow only for a resonant buildup of the electron wave function in the potential well with localization times shorter than the tunneling times. This will lead to an increase in the electron probability amplitude inside the forbidden region, resulting in a greatly enhanced barrier transmission coefficient. We believe

that this type of the electron resonant transmission is responsible for the structure resolved in our tunnel characteristics. It is then appropriate to consider a model which explicitly shows how such resonances can affect the conductivity of the tunnel junctions.

5.4 Resonant tunneling through impurity states

For simplification let us consider a tunneling process in which the insulating layer contains only one impurity, having an allowed energy level of a magnitude eV_0 , inside the barrier. For further simplification let us assume that the metal electrodes are at 0 K and that the barrier potential can be represented by its average value Φ (fig. 5.13a). As the bias is established between the two electrodes the Fermi levels separate and the impurity level shifts linearly with the electric field. Past the threshold voltage

$$V = |V_0| + V \cdot \frac{r}{\ell}$$

(where r is the position of the impurity, ℓ , thickness of the barrier) the impurity lies above the Fermi level of the right hand electrode. In this case a new tunneling channel opens up in which electrons can tunnel from



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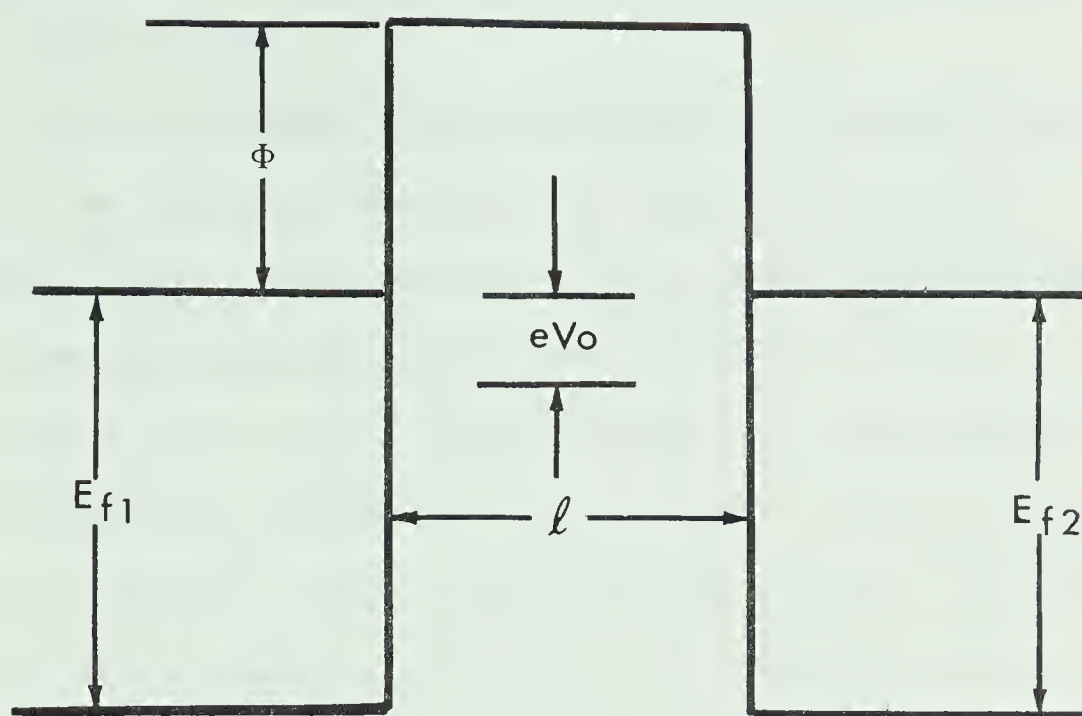
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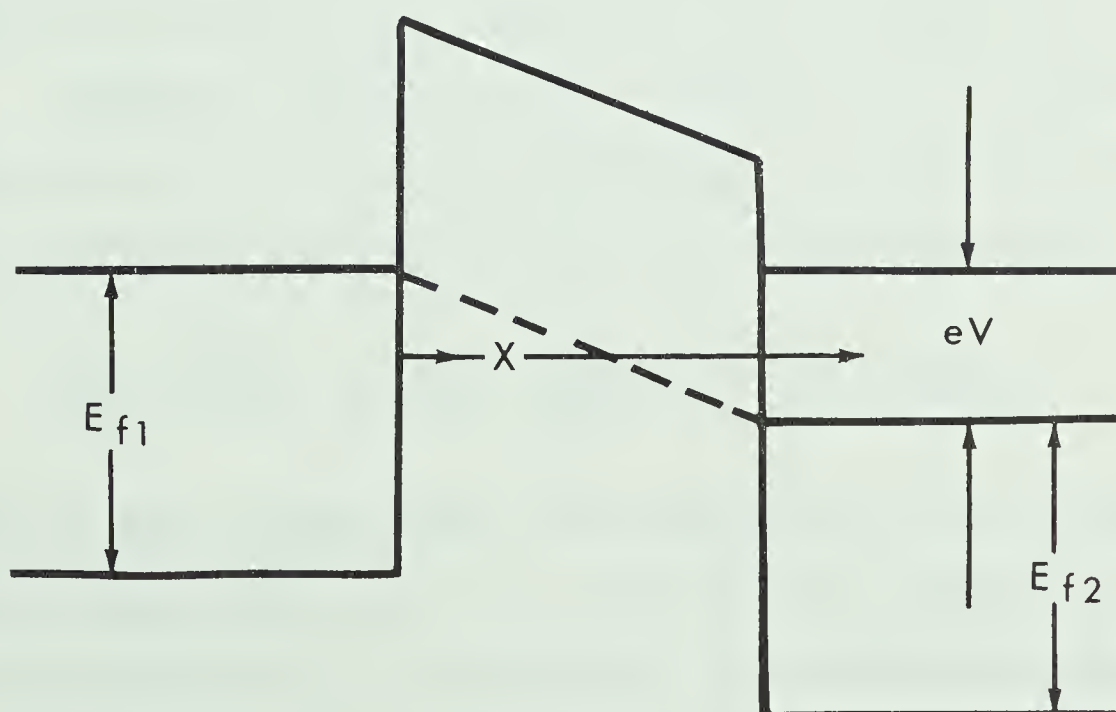
Fig. 5.13

Schematic potential for a junction having a single impurity in the middle of the barrier:

- a) no applied voltage
- b) sufficient applied voltage so that the resonance channel is opened.



a



b

left to the impurity and then from the impurity to the right (fig.5.13b).

Let us consider what happens to the wave function of an electron with energy equivalent to the trapping level. The incoming wave after penetration decays exponentially inside the barrier. As it approaches the trap it resonates with a large amplitude inside the potential well. After a partial localization it decays again exponentially towards the other side of the barrier. By moving the potential well to the middle of the barrier the amplitude of the incoming wave can be made equal to that of the outgoing wave (Bohm, 1964). For electron energies different from the resonance level the wave function decays exponentially in the usual way while passing through the barrier.

Gadzuk's (Gadzuk, 1970) treatment of the described model gives the following expression for the ratio of conductivities with and without the trapping center:

$$\frac{\sigma_R}{\sigma_N} = \frac{N_i A_i}{A_s} \cdot \frac{1}{2} \exp\left(\ell \sqrt{\frac{2m}{\hbar^2}} \phi^{\frac{1}{2}}\right) \cdot \theta(|V| - 2|V_0|) \quad (5.1)$$

where it was assumed that the resonance occurs in the low voltage region ($eV \ll \phi$) and that the impurity lies in the mid-plane of the barrier. N_i represents the number of impurities with an effective cross section A_i . A_s gives the junction area. $\theta(x)$ is a usual step

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function. Setting $N_i A_i / A_s = 1$, $\Phi = 1$ eV, $\ell = 30$ Å the ratio of σ_R / σ_0 at the threshold of impurity assisted tunneling is $\sigma_R / \sigma_N = 2 \times 10^{16}$. However, in real situation this favourable ratio is reduced considerably by smallness of $N_i A_i / A_s$.

The calculation of the resonant conductivity with a single impurity is a great simplification of the tunneling problem. In practice the impurities are distributed over the whole volume of the insulating layer. It is then reasonable to expect that the resonance levels will be smeared out and the sharp conductivity increase will be further reduced.

Gadzuk's calculation shows that the smearing effect indeed reduces the conductivity increase. Fig. 5.14a illustrates the ratio of the distributed impurity conductance to the clean junction as a function of applied voltage, treating the impurity level parametrically ($N_i A_i / A_s = 1$). Fig. 5.14b shows the effect of the barrier width on σ_R / σ_N . The broadening of σ_R / σ_N is due to the presence of a finite electric field in the barrier which shifts the bound state energy of an impurity by an amount of the order of the voltage drop at the corresponding impurity site. To avoid complete blurring of the resonance effect it is important that the impurity has an energy level close to the Fermi level and that it is located in a few



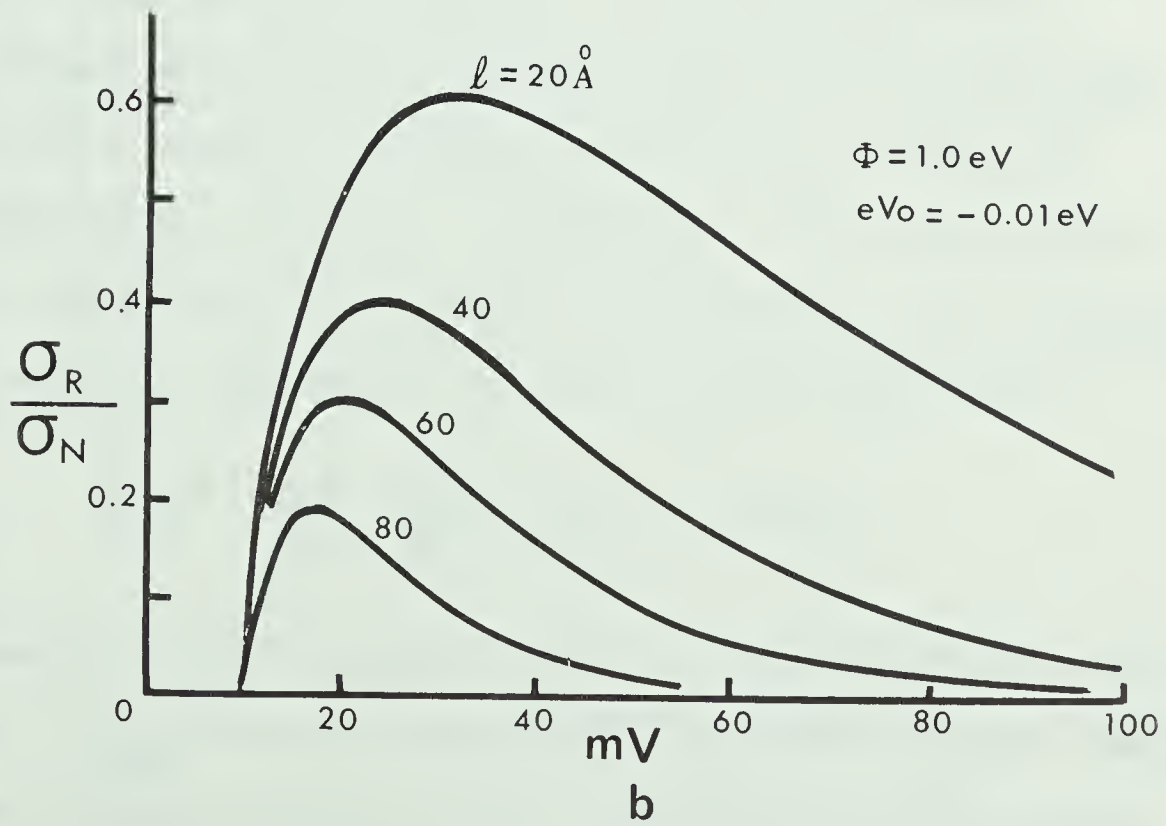
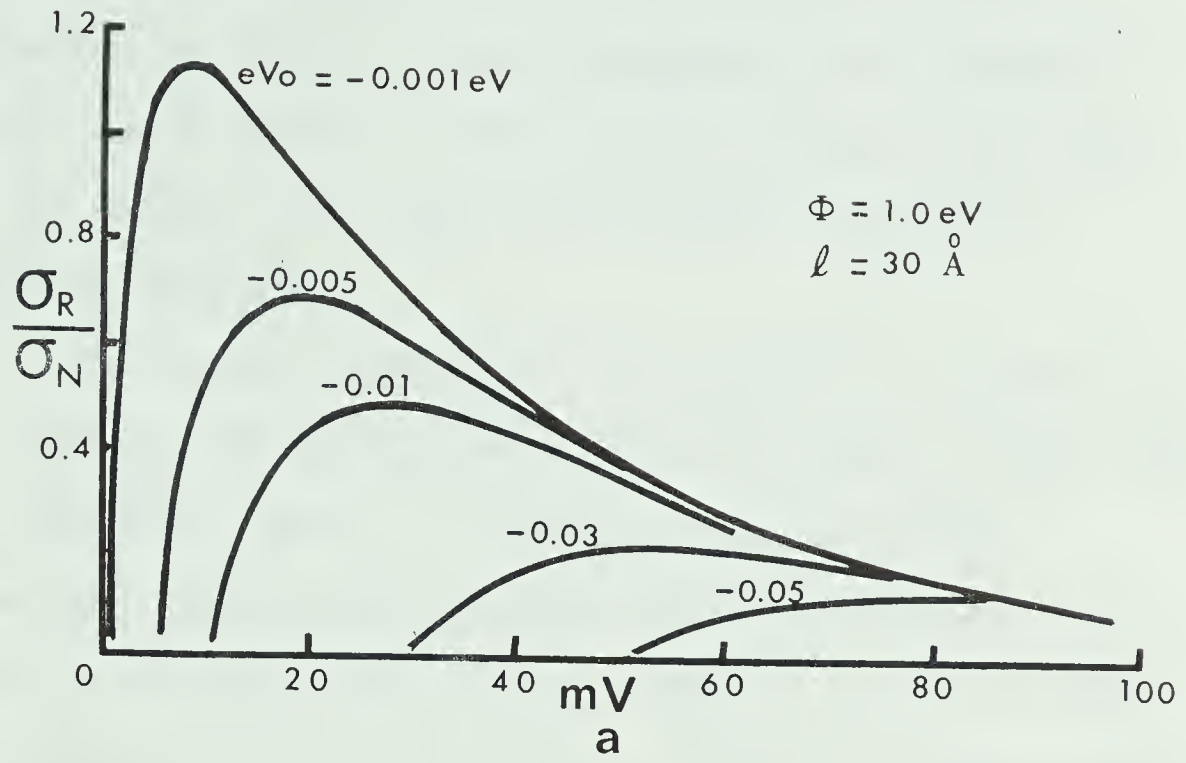
Figure 1. The function $f(x)$ and its derivative $f'(x)$.



Fig. 5.14

The ratio of distributed impurity conductance to the clean junction conductance as a function of voltage:

- a) impurity level treated parametrically
- b) thickness of the barrier treated parametrically.





neighbouring atomic planes inside the barrier. Impurity clusters lying near the interface yield a contribution which is very asymmetric with respect to the applied bias. This follows because the shift of the energy level with the applied voltage is polarity dependent.

We should note that the presented treatment is one dimensional and assumes that the impurity has only one resonance level. In reality the attractive potential associated with the impurity can have more than one allowed level with a result that the tunneling characteristics will show a series of peaks which may or may not interact with each other to bring in additional smearing effect. A three dimensional treatment by Hurault (Hurault, 1971) of the resonant electron tunneling predicts that the transmission coefficient varies as a Lorentzian with the peak at the resonance energy level. The width of the Lorentzian is equal to the width of the virtual bound state

$$|T_R|^2 \sim \frac{\Gamma^2}{(E - E_R)^2 + \Gamma^2} \times |T_{\text{imp}}|^2$$

where E_R is the resonant level, Γ - width of the level and $|T_{\text{imp}}|^2$ is the resonance enhancement factor dependent on the position of the impurity and its concentration. A calculation by Combescot (Combescot, 1971) confirms Hurault's result.

5.5 Discussion

On the basis of the experimental evidence presented in section 5.3 we have concluded that the interaction between the tunneling electron and the trapped impurity is responsible for the appearance of the additional structure in our tunnel junctions. Schmidlin (Schmidlin, 1965) analyzed the effect of the trapping centers on the barrier profile and found that throughout a low voltage region a positive ion substantially reduces the barrier height in its locality. At large biases the effect of the impurity is "smothered" out if the ion is close to the positive electrode. The local decrease of the barrier height around the impurity can then be instrumental in establishing a resonant transmission of electrons across the barrier via intermediate energy levels existing inside the barrier.

With these considerations, the changes produced in the general behaviour of the junctions by annealing or by applying a DC bias can readily be explained by allowing the charged impurities to migrate through the insulator. The change in the oscillatory pattern while a current was passed along the electrode is attributed to a redistribution of charges existing at the metal-insulator interface.

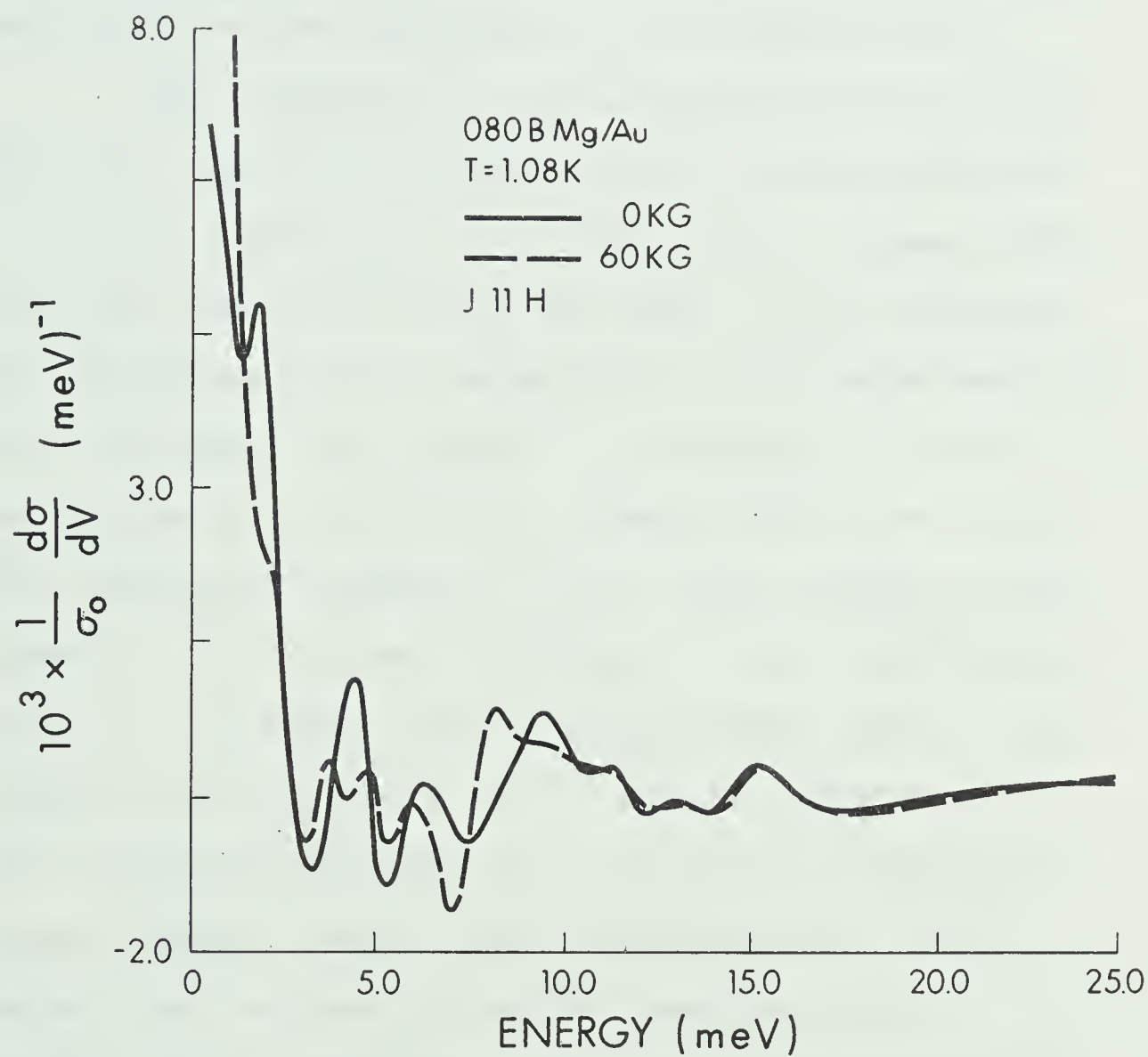
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A convincing confirmation of the resonant impurity assisted tunneling arises from the observation of the behaviour of the localized energy levels under the influence of a magnetic field. In fig. 5.15 we show the second derivative curve of a previously shown junction (fig. 5.9) measured at 0 kG and 60 kG, with a field oriented parallel to the tunneling current. The characteristics were obtained after the junction was annealed at room temperature. Even though the oscillations when compared to the first measurement did not seem to exist, a 10 fold increase in sensitivity resolved the weak structure. The prominent feature of the 60 kG curve in fig. 5.15 is the appearance of two peaks at ~ 5 meV as a result of the spin splitting of the previously degenerate atomic level (0 kG). The effective g factor obtained from the separation is $g = 2.75$. With the exception of the peak at ~ 16 meV which is identified with inelastic phonon emission (Klein et al, 1973) the other peaks appear to be shifted or broadened under the influence of the magnetic field. A small energy difference in the separation of the peak at 5 meV suggests that the strength of the magnetic field was not sufficient to achieve complete splitting of the other atomic levels. Esaki et al (Esaki et al, 1968) reported a similar observation of localized energy levels in the forbidden gap of PbTe. Oscillations



Fig. 5.15

Illustration of the spin splitting of an
impurity level.





in the tunnel characteristics of Pb/O/Pb were reported as well (Yanson et al, 1971). These were directly correlated with the impurity contamination of the barrier by a layer of uracil. It was assumed that tunneling through localized energy levels was responsible for the occurrence of the oscillations.

The discussion in the preceding section shows that the effect of the impurities is most pronounced if they are distributed in a few atomic planes which are well separated within the depth of the insulator. The sharpness and the separation of the experimentally observed peaks then leads to a conclusion that the impurities do not interact strongly with each other. The lifetimes broadening of the atomic levels of the order of 1 meV gives an estimate on the localization time of an electron inside the potential well. The time on the order of 6×10^{-13} sec is comparable to the accepted magnitudes of the barrier transmission times (Gadzuk, Lucas, 1973; Thornber et al, 1967). Recall that we have "ab initio" required such a relationship. The bias region of the occurrence of the oscillations confirms the theoretical prediction that their observation is more likely if the intermediate energy levels are situated in the vicinity of the Fermi level.

Even though the origin of the impurities has not been established a few considerations may help to elucidate this question. The observation of a structure in Mg junctions irregardless of the top electrode and of the barrier leads to two possibilities or a combination of both. Into the first category we classify a contamination of the barrier (while it was grown) by foreign atoms. This includes the unavoidable adsorption of residual gases inside the vacuum system. Shen (Shen, 1968) suggested that various impurities (Al, Ni, Pt) can be introduced into the insulating layer if the glow discharge method is used for the barrier formation. The contamination was caused by materials sputtered from the electrodes. The Sn-Pb and Sn-Sn junctions showed several sharp, peaklike 1% structures in the conductance of the tunnel junctions which he identified with randomly distributed energy states in the barrier.

The second possibility leads to an assumption that the insulating barrier intrinsically contains trapping centers arising from its nonstoichiometric growth (Fisher-Giaver, 1961; Pollack, Morris, 1964; Esaki, et al, 1968; Sasaki, 1960). Stevenson and Hensley (Stevenson, Hensley, 1961) concluded that MgO tends to exist in the form of an n-type semiconductor. The donors responsible for this behaviour

were similarly associated with the nonstoichiometric composition of the oxide. We suggest further experiments in which the procedure of sample preparation would be altered in order to eliminate the suspected reasons behind the contamination of junctions. We, similarly, leave open the answer for the disappearance of the oscillations with the oil doping of the junctions. We suggest either a binding of uncompensated Mg ions into complex organic molecules or a much simpler reason, arising from preventing the sputtering of materials from the discharge electrodes by formation of a thin layer of oil on the surface of the electrodes.

CHAPTER 6

TUNNELING INTO BISMUTH

6.1 Quantum size effect in Bi

There has been a considerable interest in Bi, both theoretical and experimental (Fal'kovskij, 1968). Its interesting properties result largely from its carriers which are very light and few in number. The fermi level of the electrons is ~ 25 meV (holes ~ 11 meV) and the effective mass along some crystal direction is two or three orders of magnitude smaller than the free electron mass (Fal'kovskij, 1968). Consequently the electronic de Broglie wavelength can be as large as $300 \text{ \AA}$ or $400 \text{ \AA}$. In comparison the de Broglie wavelength in metals is on the order of the lattice period which is at the most a few $\text{\AA}$. If the de Broglie wavelength of the conduction electrons becomes comparable to the physical dimensions of the sample, the electronic energy spectrum should become discrete (quantum size effect) with the separation between the energy levels being determined by the sample thickness (Tavger, Demikhovskij, 1969). The main features of size quantization can be derived from a model in which the electrons and the holes are regarded as independent particles moving in an infinite

square well potential. The single particle wave function for a film of thickness L_z can then be written as

$$\psi_{n k_x k_y} = \left(\frac{2}{L_z L_x L_y} \right)^{1/2} \sin \frac{n\pi z}{L_z} \cdot \exp(ik_x \cdot x + ik_y \cdot y) \quad (6.1)$$

where $0 \leq z \leq L_z$, and the film has infinite dimensions in the y and z directions. The corresponding energy spectrum is

$$E_{n k_x k_y} = n^2 E_0 + \frac{\hbar^2 k_x^2}{2m_x} + \frac{\hbar^2 k_y^2}{2m_y} \quad (6.2)$$

where

$$E_0 = \frac{\hbar^2 \pi^2}{2m_z L_z^2}$$

$$n = 1, 2, 3, \dots$$

Thus while in a bulk crystal, the electron states are given by points which fill the Fermi sea quasi-continuously; in a thin film the Fermi surface breaks up into allowed subsheets parallel to k_x - k_y plane. Each subsheet corresponds to a discrete value of the wave vector along the quantized direction of the film (Garcia, et al, 1972). These consequences have been investigated with regard to electrical conductivity, optical properties, galvanomagnetic phenomena, paramagnetic susceptibility, superconductivity and tunneling

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Chapter 1

Introduction to the Study of Psychology

Psychology is the scientific study of behavior and the mind. It seeks to understand the biological, psychological, and environmental factors that influence human behavior.

The field of psychology is divided into several subfields, including:

Developmental Psychology

Developmental psychology studies the changes in behavior and the mind that occur over the course of a person's life.

Experimental psychology involves the use of controlled experiments to study behavior and the mind.

Behavioral psychology focuses on the study of observable and measurable behaviors.

Biological psychology examines the relationship between the brain, the nervous system, and behavior.

Health psychology studies the psychological factors that influence physical health and illness.

phenomena (Tavger, Demikhovskij, 1969; Larson, 1971).

One of the possible methods of direct experimental observation of the quantization of the transverse motion energy in a film is the use of tunneling of the electrons in a sandwich made of the investigated films (Gogadze, Kulik, 1965; Kümmel, 1968). In the tunnel junction, the films of quasi-discrete energy spectrum are separated by a potential barrier. When an external field is turned on, the energy levels of one film shift relative to the levels of the other film. Assuming elastic transmission, the current through the barrier will arise whenever the populated levels of one film lie opposite the free levels of the other film. As a result, a current-voltage characteristic in the form of a series of peaks is obtained. The period of oscillations is approximately

$$\Delta E = \frac{\pi \hbar}{L_z} \sqrt{\frac{2E_f}{m^*}} \quad (6.3)$$

where m^* is the effective mass of the carrier. The upper bound on the amplitude of the oscillations is estimated to be

$$\frac{I^{OSC}}{I_{non}} \leq \frac{\Delta E}{E_f} \quad (6.4)$$

(Gogadze, Kulik, 1965). It is illustrative to estimate the order of magnitudes involved. In order that the

oscillations would be observable let us require that

$$\frac{I^{\text{OSC}}}{I_{\text{non}}} \sim 10^{-1}.$$

This depending on the Fermi energy puts an upper limit on the thickness of the film. Table 6.1 illustrates the calculated values of the required thickness and correspondingly obtained periods of oscillations, ΔE .

Table 6.1

Thickness and periodicity of oscillations

<u>Material</u>	<u>m^*</u>	<u>E_f</u>	<u>Required thickness</u>	<u>Calculated ΔE</u>
typical metal	m_0	1 eV	120 Å	98 meV
Bi electrons	$10^{-2} m_0$	25 meV	7400 Å	2.50 meV
Bi holes	$0.7 m_0$	15 meV	1140 Å	1.50 meV

m_0 is the mass of the free electrons.

The thickness range in Bi is considerably relaxed because of the small Fermi levels and light masses of the carriers. Thus according to theoretical predictions it is possible to observe the QSE directly by tunneling. However, it is obvious that this favourable prediction is further minimized through thermal smearing and scattering of the carriers by impurities and diffuse boundaries. It is then necessary to keep the films sufficiently homogeneous and pure. Tunneling into single crystals

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or films containing large grains of well defined orientation therefore increases the likelihood of the observation of the QSE. The existence of quantized energy levels in thin metal films was well documented through ingenious interpretation of tunneling results of Jacklevic et al (Jacklevic et al, 1971). They have noticed that even though the required smoothness of the metal films is not experimentally feasible, certain energy levels (for instance at the band edge) are stationary with respect to thickness perturbations. These then are easily determined by tunneling experiments.

A direct observation of the quasi-discrete energy level spectrum by tunneling was claimed by Russian experimentalists (Korneev et al, 1970; Lutskii et al, 1966). Korneev et al have observed oscillations in Ag-Bi structures in which the electrodes were condensed onto two separate mica substrates and pressed together. The measurements were performed at nitrogen temperatures. The thickness of Bi films was greater than 1000 Å. Lutskii et al reported the observation of the QSE in structures in which the thickness of the Bi films ranged between 800-1300 Å. In both cases the steplike increases in the tunnel characteristics allowed a successful correlation with the thickness of the film.

The purpose of our experiments was to reproduce these results through tunneling experiments in

systems containing Bi films in which the insulating layer was formed by a solid dielectric.

6.2 General considerations

The investigations were performed on Al/Bi, Mg/Bi, Bi/Bi and Bi/Pb junctions. They were prepared according to the procedure described earlier (section 3.2). The substrates usually were heated to 80°C by a resistive heater in order to promote formation of large grains in the evaporated film. Even though Bi films evaporated onto glass slides generally are polycrystalline, the trigonal axes of their grains are usually within 20% of the film normal (Komnik, Bukhstab, 1968). Condensation of Bi films onto heated mica creates larger crystallites, the trigonal axes of which are perpendicular to the substrate (Komnik, Pilipenko, 1971). Hauser and Testardi (Hauser, Testardi, 1968) reported similar observations. Electron microscope study showed that the lateral sizes of the microcrystals were on the order of 1500 Å - 3000 Å. The extent of grain formation was not very critical on the evaporation rate. The annealing of films during oxidation did not increase the grain sizes appreciably (20%-30%).

The thickness of Bi electrodes ranged between 1500 Å - 15000 Å. Films thinner than 1500 Å after oxidation had very high resistances ($>5 \text{ k}\Omega$).

Junctions made of these in most cases were not stable and were easily destroyed by biasing them only to a few meV. The counterelectrodes of Al, Mg, Pb were approximately 1000 - 5000 Å thick.

The detection of an energy gap in Pb by tunneling gave us a confidence that the dominant mechanism of a current transport across the oxide of Bi was due to tunneling. The observation of inelastic phonon assisted tunneling in Bi/Bi samples similarly led us to believe that by oxidation of Bi in oven we could prepare "good" tunnel junctions.

6.3 Discussion of results

Early measurements on Bi/Bi junctions showed a reproducible oscillatory type structure in the vicinity of zero bias. We illustrate this in figs. 6.1 and 6.2. Fig. 6.1 shows the conductance curves for three Bi/Bi junctions. The Bi films in junctions 007 and 016 were 5000 Å thick. The films in 001 were 4000 Å thick. The corresponding derivatives $d\sigma/dV$ are in the next figure (fig. 6.2). The amplitudes



Fig. 6.1

Conductance vs energy for three Bi/Bi
junctions. The thicknesses of films were
following :-

001 - 4020 Å/4020 Å

007 - 5360 Å/5360 Å

016 - 5420 Å/5360 Å

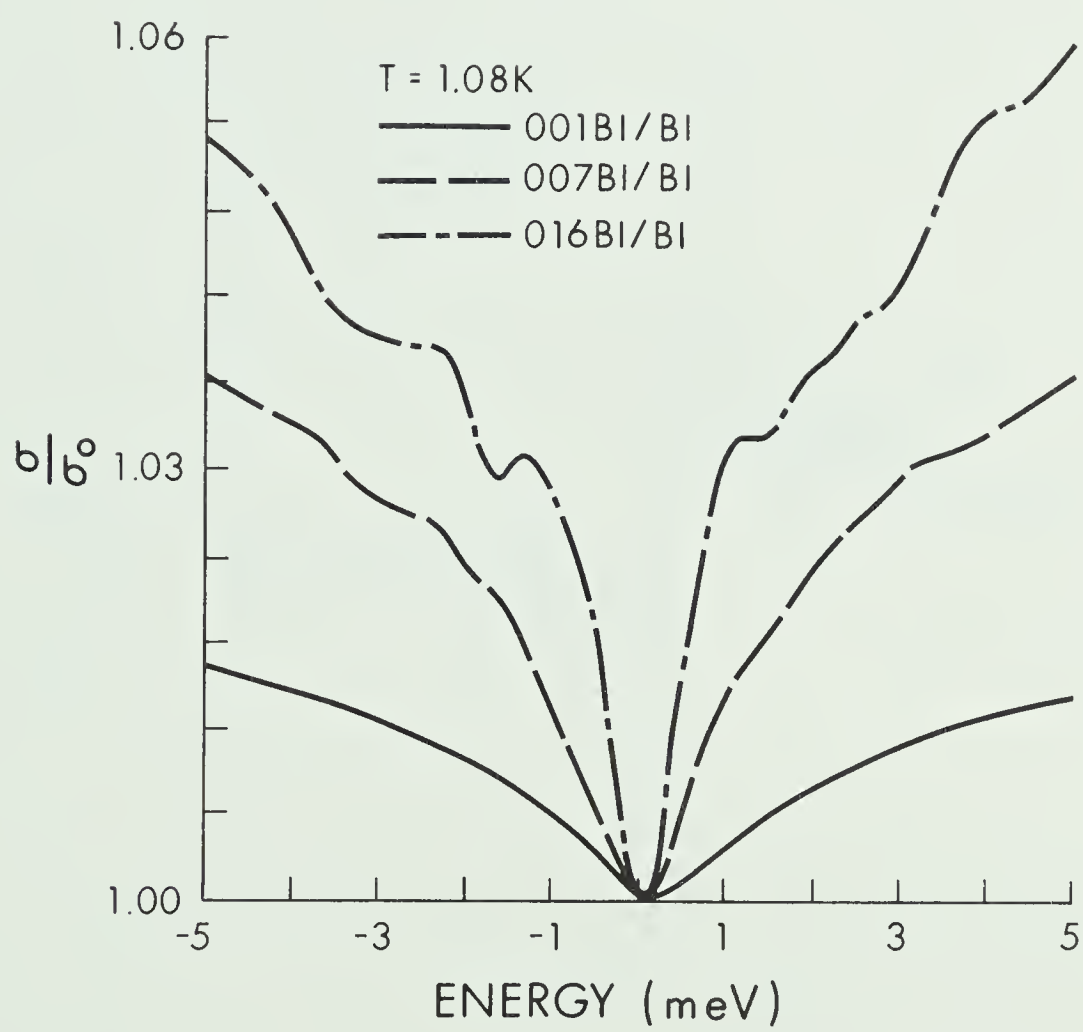
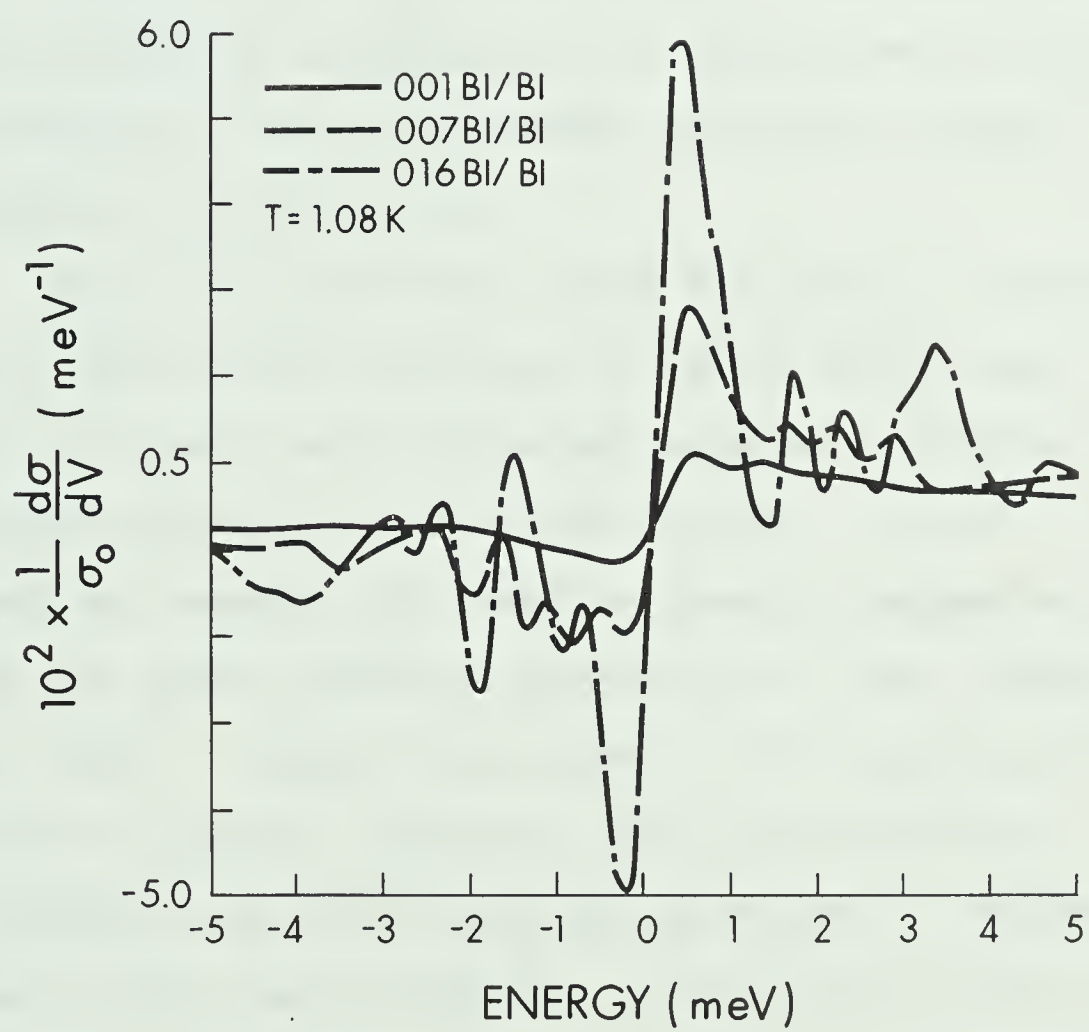




Fig. 6.2

$d\sigma/dV$ vs energy for three Bi/Bi
junctions



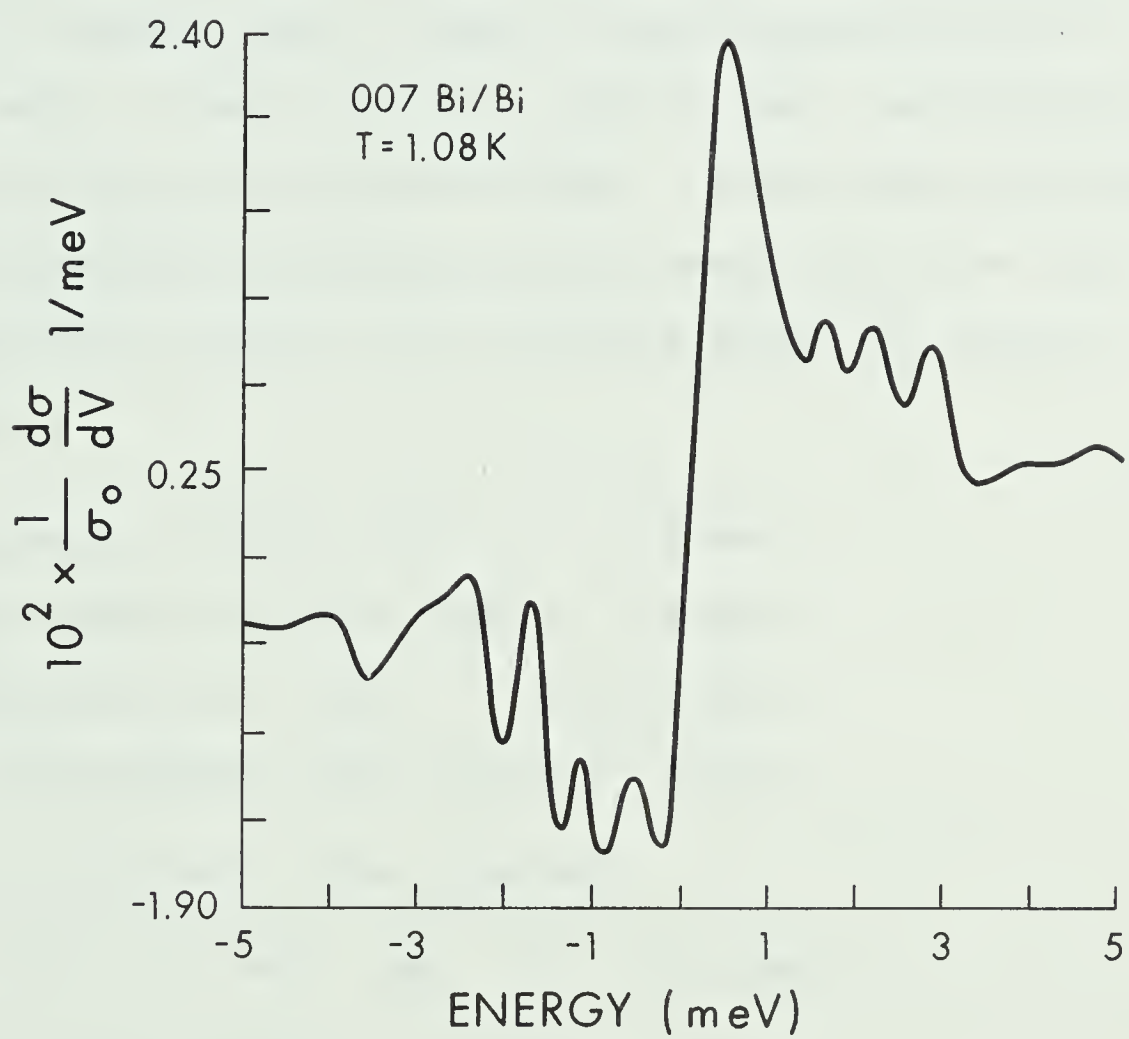
of oscillations in 001, in comparison to the two other junctions, are small and barely visible. For positive applied voltages (top film positive) the oscillations had practically the same periodicity. This, however, was not true for the bias voltages of negative polarity (top film negative). The explanation of this effect is probably due to difference in the film structure, since the bottom films were always subjected to an annealing.

Fig. 6.3 illustrates $d\sigma/dV$ for 007 in a greater detail. The general features of oscillations seen in fig. 6.3 were well reproduced even in junctions where the electrodes were 15000 Å thick. In all samples the regular oscillations always disappeared beyond the phonon emission threshold at 3 meV (Rowell et al, 1969). Taking into account this reproducibility we believe that the structure cannot be connected with impurity assisted tunneling discussed in Chapter 5. However, since the periodicity of oscillations did not change with increased thickness of Bi films, we can immediately conclude that the structure cannot be connected with the observation of quantum size effect.



Fig. 6.3

$d\sigma/dV$ vs energy for 007 Bi/Bi shown separately



6.4 Phonons in Bi

The observation of phonon emission by tunneling in carefully prepared single crystals of Bi has been reported by Esaki et al (Esaki, et al, 1968a). The conductance characteristics of Bi/Al₂O₃/Au tunnel junctions, in which Bi was oriented along its trigonal axis, showed a set of humps located approximately at 3 ± 1 meV, 6 ± 1 meV, 10 ± 1 meV and 14 ± 1 meV, regardless of the polarity of applied voltage. These were correlated with previously measured phonon energies of the four propagation modes in the trigonal direction (Kotov et al):

transverse acoustic (TA) = 4.8 meV ,

longitudinal acoustic (LA) = 7.4 meV ,

transverse optic (TO) = 12.6 meV ,

and longitudinal optic (LO) = 13.4 meV ,

at the Brillouin zone boundary,

and TO = 9.2 meV and LO = 12.5 meV

at the zone center.

Peaks in $d\sigma_e/dV$ at 3 and 12 meV reflecting the inelastic excitation of Bi phonons in Al/Bi junctions were observed by Rowell et al (Rowell, et al, 1969).

Results similar to those quoted above were obtained in our samples as well. However, in contrast



Fig. 6.4

Observation of inelastic phonon assisted tunneling in a Bi/Bi junction prepared on mica. The numerals show the location of phonon peaks.

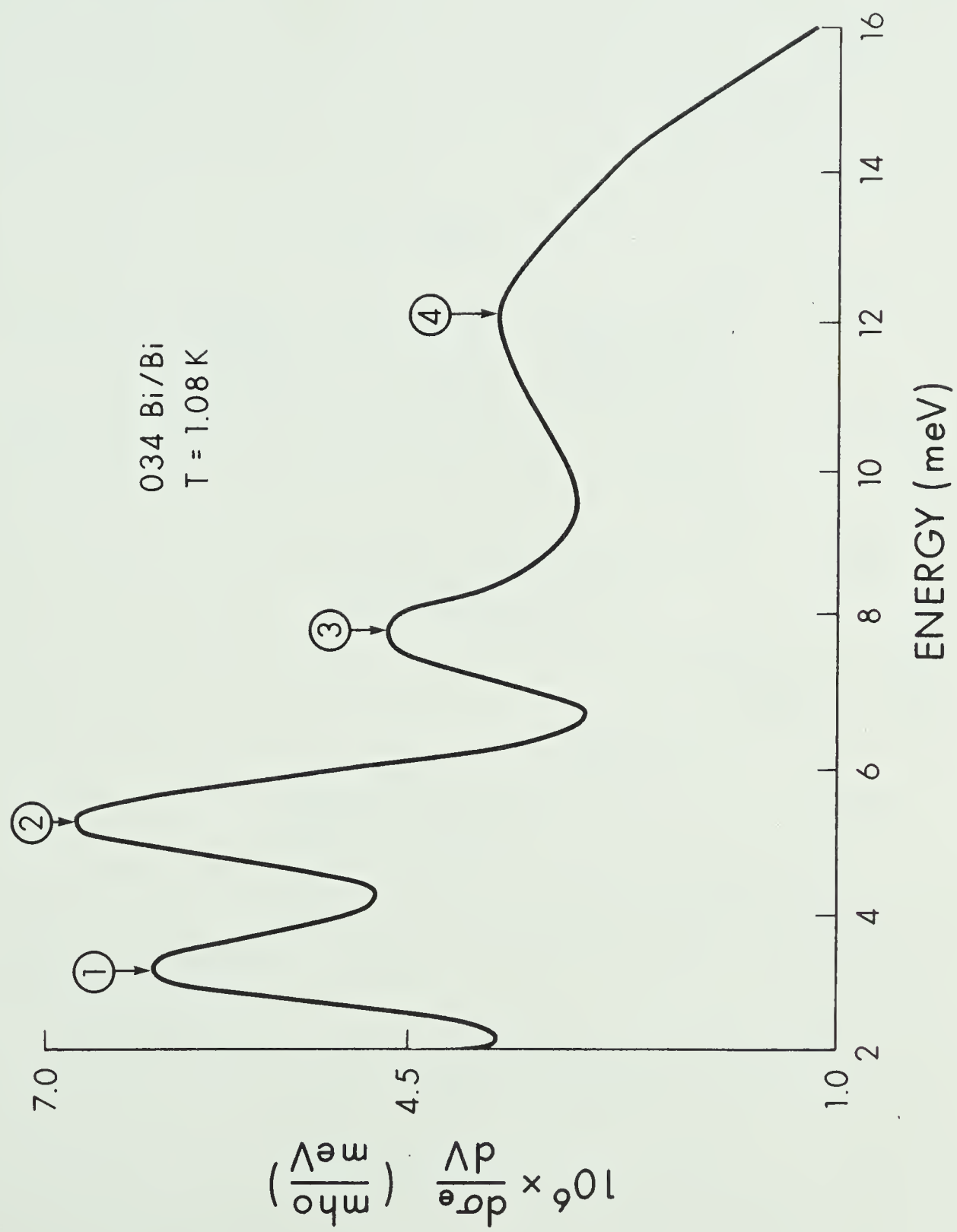




Fig. 6.5

Observation of inelastic phonon assisted
tunneling in a Mg/Bi junction. The
numerals show the location of phonon peaks.

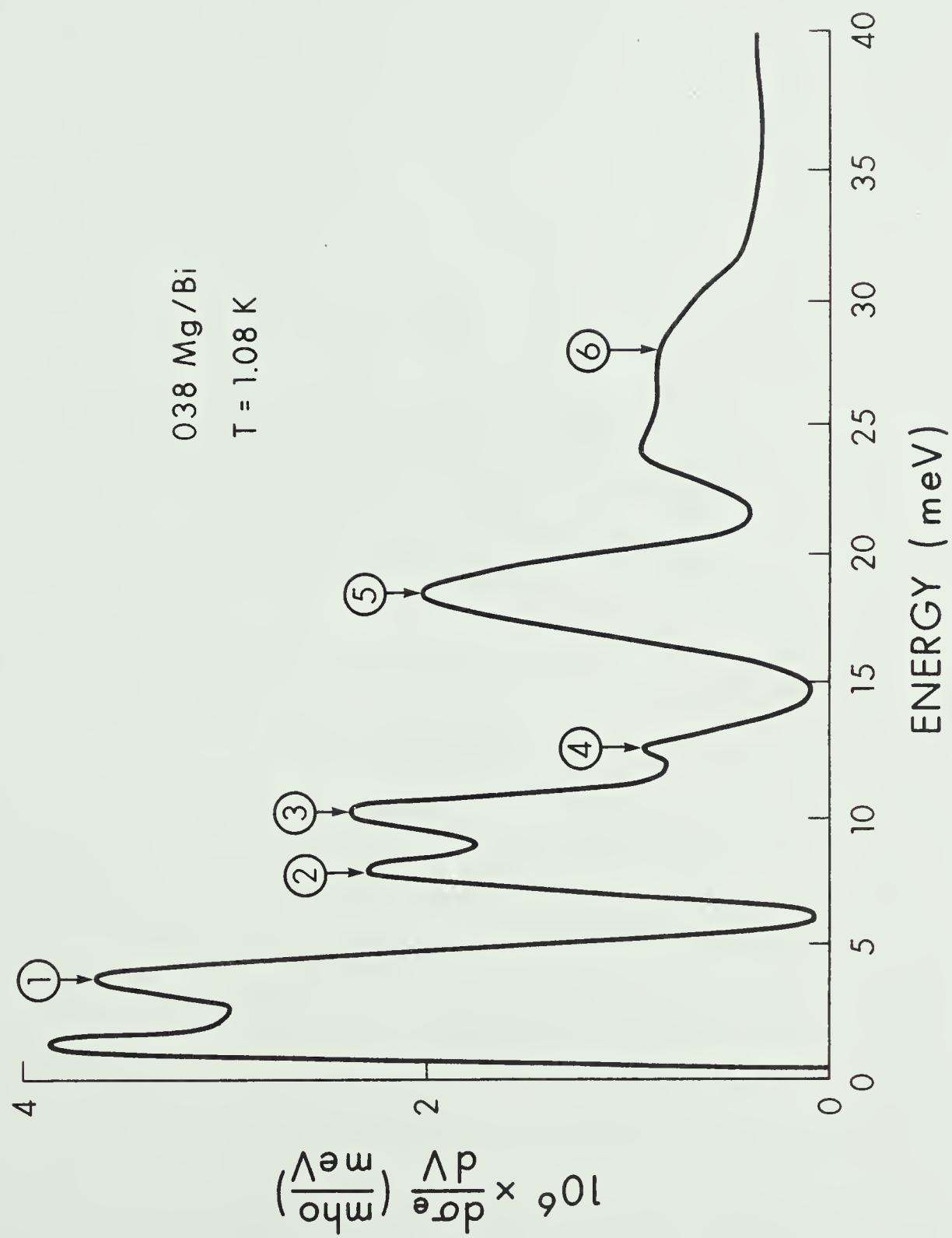
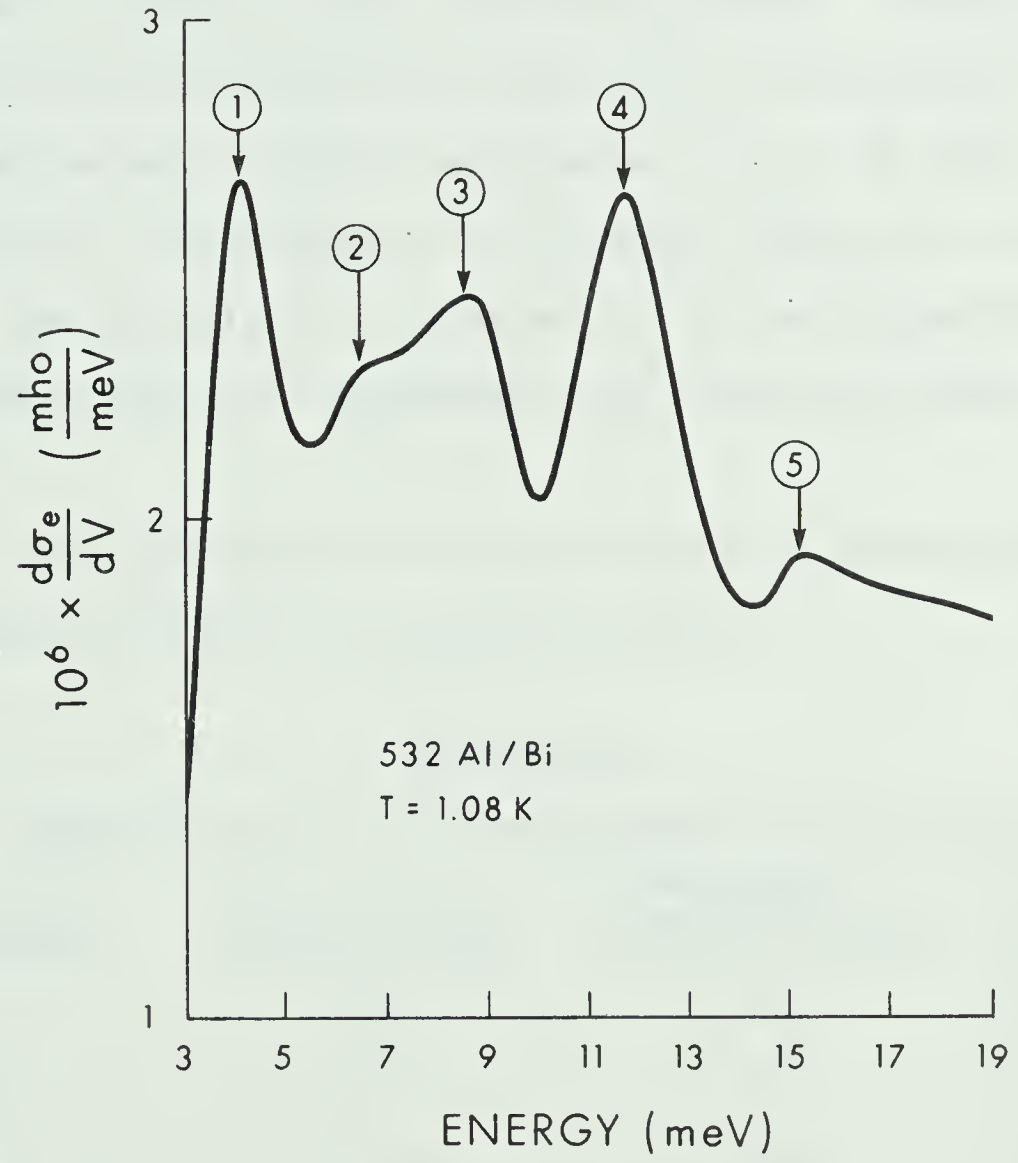




Fig. 6.6

Observation of inelastic phonon assisted tunneling in an Al/Bi junction. The numerals show the location of phonon peaks.



to the observation of Rowell et al, we were able to detect phonons which energetically lie between 3 and 12 meV.

According to Esaki et al junctions with polycrystalline Bi films did not exhibit the fine phonon structure in their tunnel characteristics. Furthermore, they did not see any structure in junctions, the resistances of which were below 5 k Ω . In comparison the resistances of our samples were less than 5 k Ω . The detection of phonons in our polycrystalline Bi films therefore complements the results of Esaki et al.

The assignments of phonon emission thresholds according to Kotov et al are following :-

Table 6.2

Identification of phonon peaks in Bi/Bi junction

<u>Peak number</u>	<u>Position(meV)</u>	<u>Possible identification</u>	<u>Cryst. direction</u>
1	3.1	LA	2 fold axis
2	4.8	TA	3 fold axis
3	7.8	LA	3 fold axis
4	12.3	TO,LO	3 fold axis

Similar identification is performed in a Mg/Bi junction (fig. 6.5).

Table 6.3

Identification of phonon peaks in Mg/Bi

<u>Peak number</u>	<u>Position (meV)</u>	<u>Possible identification</u>	<u>cryst. direction</u>
1	3.3	LA	2 fold axis
2	7.7	LA	3 fold axis
3	9.7	TO	3 fold axis
4	12.4	TO, LO	3 fold axis
5	18.4	transverse Mg	
6	27.5	longitudinal Mg	

The unmarked peak is due to zero bias anomaly.

Finally, we present the results of tunneling into an Al/Bi junction (fig. 6.6).

Table 6.4

Identification of phonon peaks in Al/Bi

<u>Peak number</u>	<u>Position (meV)</u>	<u>Possible identification</u>	<u>Cryst. direction</u>
1	3.7	LA	2 fold axis
2	6.5	TA	3 fold axis
3	8.5	LA?	3 fold axis
4	11.4	LO	2 fold axis
5	15.1	2 phonon processes?	

When determining the exact peak positions above a small correction factor (.18 meV) due to superconductivity of the Al-electrode was subtracted from the experimentally measured peak positions. The peak at 6.5 meV is identified only tentatively in the view of uncertainty in exact determination of maximum in $d\sigma_e/dV$. The peak at 8.5 meV is above the LA phonon (7.3 meV) emission threshold. Both peaks, however, at 4.2 K merged into a broad shoulder around 8 meV which is in the vicinity of the excitation energy of the LA phonon. The common feature of all three samples is the appearance of phonon peaks in the vicinity of 3 and 12 meV. This suggests that the coupling between electrons and phonons is strongest at these energies. We expect that the resolution of phonon peaks at different energies depends on the size and orientation of grains comprising the evaporated Bi film.

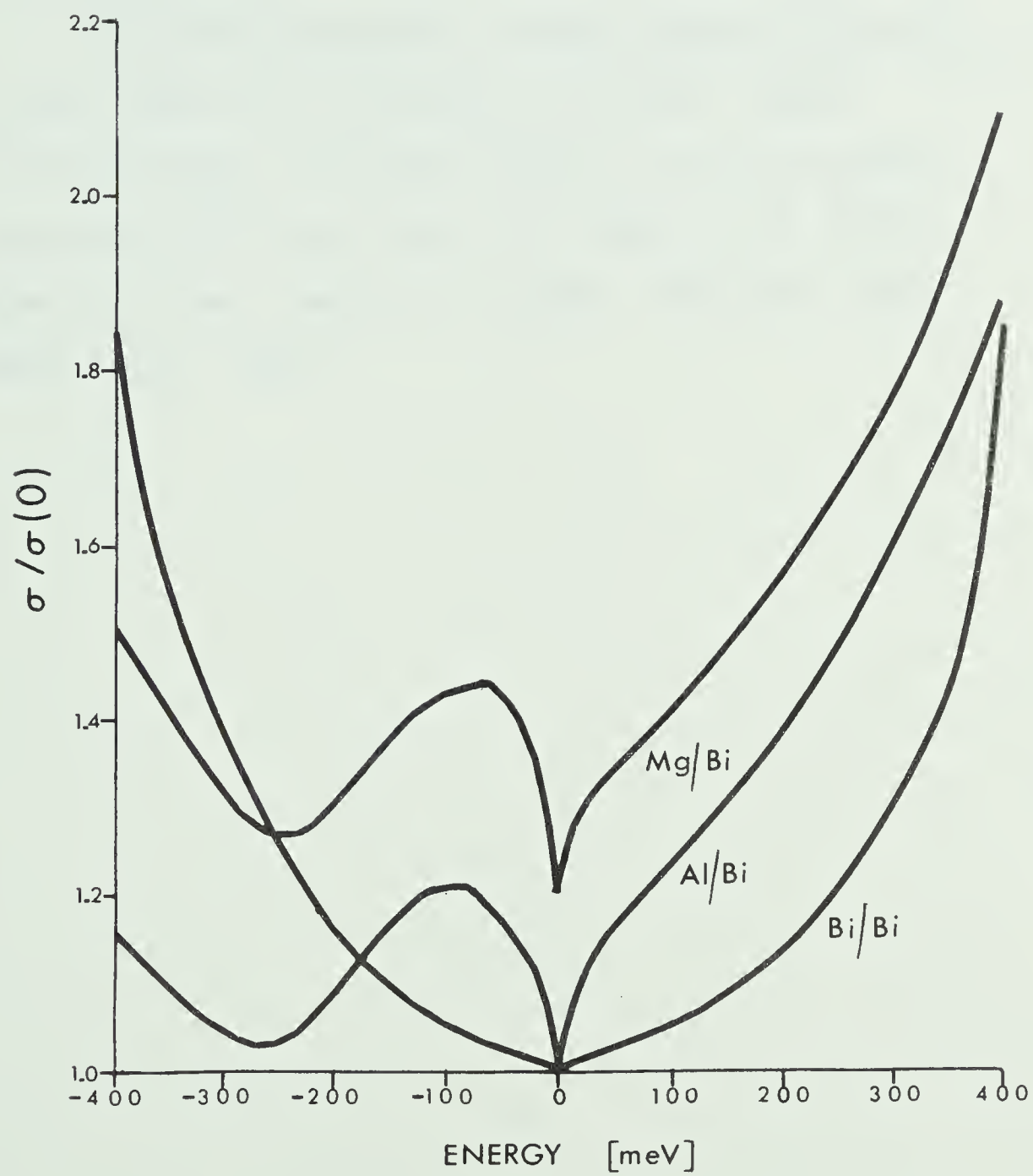
6.5 Other interesting effects

In connection with attempts to observe QSE in Bi we have performed tunneling experiments in which the junctions were biased up to 500 meV. All Al/Bi and Mg/Bi junctions have shown the characteristic W-shape (Fig. 6.7). The Bi/Bi junctions on the other hand show the more parabolic shape associated with



Fig. 6.7

Normalized conductance vs energy for typical Al/Bi, Mg/Bi and Bi/Bi junctions. The Mg/Bi curve has been displaced upwards by 0.2 for clarity. Negative bias indicates that the bottom layer is negative with respect to the counterelectrode.



symmetrical tunnel junctions. We feel that the W-shape arises from the large difference in Fermi energies between the base layer and Bi counter-electrode.

In the intermediate energy range (<100 meV) we have observed a structure in Bi/Bi, Mg/Bi, Bi/Pb and Pb/Bi junctions which in certain extent correlated with the known band edges of Bi determined by other observers (Hauser, Testardi, 1968; Esaki et al, 1965).

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Discussions

The experimental work presented in this thesis is divided into three chapters.

In Chapter 4 we have presented the results of measurements of small conductance decreases occurring around zero bias. A recent theory (Trofimenkoff et al, 1972) has explained these through non-equilibrium treatment of the tunneling process. In particular, the related structure in σ and $d\sigma/dV$ have been accounted for by the blocking of otherwise available electron states due to finite electron relaxation times in metal electrodes. The theory assumes that the deblocking of occupied states is through scattering of electrons via lattice vibrations and impurities. These processes are characterized by a temperature and energy dependent electron-phonon relaxation time τ_{ep} and a constant impurity scattering time, τ_i . The temperature dependence of the zero bias anomaly is described only by one parameter Γ , the knowledge of which allows one to extract the impurity scattering time τ_i , if the strength of the electron-phonon interaction is known beforehand.

We have performed detailed measurements on Mg/Mg, Mg/Au and Al/Al junctions and found that the theory agrees well with experiment. A magnetic field oriented perpendicularly to the direction of tunneling current reduced the conductance anomaly. This effect was explained on the basis of Lorentz force induced drift of tunneling electrons with which we have associated a scattering time, τ_{drift} , proportional to the strength of applied field. No observable changes in the anomaly were detected if the magnetic field was applied parallel to the tunneling current.

While investigating the zero bias anomaly we have observed additional oscillatory type structure in characteristics of some tunnel junctions. The structure was found to exist in Mg/Mg, Mg/Au and Mg/Pb type junctions, irregardless of electrode thickness and barrier preparation. With the aid of external perturbations the properties of junctions could be irreversibly altered resulting in new characteristics. Adsorption of hydrocarbons during formation of barrier layer prevented the appearance of oscillations. From these observations we have concluded that a contamination of the insulating layer by charged impurities is responsible for the observed structure. It was suggested that the impurities could alter the barrier profile in

such a way as to allow for a resonant transmission of tunneling electrons. The effect of external perturbations is then understood on the basis of rearrangement of impurities inside the barrier. Another possible explanation of the observed effect arises if we consider a creation of space charge trapping clusters, which could be instrumental in capture of tunneling electrons. However, until the exact nature of impurity contamination is not found, the results of discussion given in Chapter 5 will remain purely speculative.

In Chapter 6 we have briefly commented on an unsuccessful attempt to observe quantized energy levels of Bi by tunneling. As a byproduct of measurements, we have observed the excitation of phonons in polycrystalline Bi films with Bi/Bi, Mg/Bi and Al/Bi junctions. These results augment the previously published data and simultaneously provide better resolution for some of the observed peaks. The high energy conductance curves (~ 500 meV) of Al/Bi and Mg/Bi junctions displayed the usual W-shape associated with such junctions. On the other hand, Bi/Bi junctions showed characteristics which are typical of symmetrical junctions. This interesting result requires further experiments for its proper interpretation.

7.2 Suggestions for further work

Concerning the zero bias anomaly we propose to investigate these areas as possible extensions of the presented work.

Evaluate the dependence of the zero bias anomaly on the crystal structure of the metal electrons. In particular, we would expect a correlation between the magnitude of the conductance dip and the anisotropy in the electron-phonon relaxation time. This, of course, requires a preparation of single crystal junctions. We include here the dependence of the zero bias anomaly on film thickness. The experimental results gave qualitative agreement with the theory. A more detailed investigation should possibly extract the amount of blocking due to decreased film thickness. In connection with this we suggest backing of electrodes with a silver layer in order to change the amount of specular scattering.

A further study should show the effect of alloying on the size of zero bias anomaly. With such experiments we can change not only the impurity scattering time τ_i , but the electron-phonon coupling strength as well.

Finally, as it has already been shown (Wattamaniuk, 1972) the non-equilibrium aspect of the electron tunneling can be extended to include a tunneling into superconducting metals. In particular, for the case of two identical superconductors, the continuous increase in the tunnel current just above twice the gap edge ($T \neq 0$ K) has been explained as due to blocking of the incoming quasi-particles. It should be noted that the quasi-equilibrium theory predicts a discontinuous jump which is experimentally not observed. Further experiments are needed to clarify this situation.

Regarding the impurity assisted tunneling, the objective of further experiments is to determine the origin of barrier contamination. This requires a different method of barrier formation; thermally grown barrier eliminates a possibility of contamination through sputtering action during glow discharge. Experiments should be performed in order to determine a mechanism by which adsorption of hydrocarbons in the insulating layer prevents the occurrence of oscillations.

Since our attempts to observe the quantized energy levels directly by tunneling have failed we suggest further experiments in which surface roughness of Bi films is minimized and better controlled. This includes tunneling into single crystals of Bi.

Furthermore, tunneling in Bi/oxide/metal and metal/oxide/Bi type junctions appears to be a unique method of proper identification of a structure in characteristics of these junctions.

BIBLIOGRAPHY

- Adler, J.G. and Jackson, J.E., Rev. Sci. Instr. 37, 1049 (1966).
- Adler, J.G., Phys. Lett. 29A, 675 (1969a).
- Adler, J.G., Sol. State Commun. 7, 1635 (1969b).
- Adler, J.G. and H.J. Kreuzer, Can. J. Phys. 22, 2842 (1972).
- Adler, J.G. and Straus, J., Technical Report, University of Alberta, 1974, unpublished .
- Allen, P.B. and Cohen, M.L., Phys. Rev. B 1, 3929 (1970).
- Anderson, P.W., Phys. Rev. Lett. 11, 95 (1966a).
- Anderson, P.W., Phys. Rev. Lett. 17, 95 (1966b).
- Appelbaum, J.A., Phys. Rev. Lett. 17, 91 (1966).
- Appelbaum, J.A., Phys. Rev. 154, 633 (1967).
- Appelbaum, J.A. and Brinkman, W.F., Phys. Rev. B 2, 907 (1970).
- Appelbaum, J.A. and Shen, L.Y.L., Phys. Rev. B 5, 544 (1972).
- Bardeen, J., Phys. Rev. Lett. 6, 57 (1961).
- BenDaniel, D.J. and Duke, C.B., Phys. Rev. 152, 683 (1966).
- BenDaniel, D.J. and Duke, C.B., Phys. Rev. 160, 697 (1967).
- Bohm, D., in Quantum Theory (Prentice Hall, Inc., New York, 1951), pp. 283-295.
- Brinkman, W.H., Dynes, R.C. and Rowell, J.M., J. Appl. Phys. 41, 1915 (1970).

Burstein, E., Lundquist, S., eds., Tunneling Phenomena
in Solids (Plenum Press, New York, 1969).

Carbotte, J.P. and Dynes, R.C., Phys. Rev. 172, 476
(1968).

Carbotte, J.P. and Truant, P.T., Can. J. Phys. 52, 618
(1974).

Chen, T.T. and Adler, J.G., Sol. State Commun. 8, 1965
(1970).

Combescot, R., J. Phys. C: Solid St. Phys. 4, 2611 (1971).

Dijk, H. van, Durieux, M., Clement, J.R. and Logan, J.K.,
The "1958 He⁴ Scale of Temperatures", NBS
Monograph 10, June 17, 1960.

Duke, C.B., Tunneling in Solids (Academic Press, New York,
1969).

Duke, C.B., Phys. Rev. 159, 632 (1967).

Duke, C.B., Kleinman, G.G. and Stakelon, T.E., Phys. Rev.
B 6, 2389 (1972).

El-Semary, M.A. and Rogers, J.S., Phys. Rev. Lett. 42A,
79 (1972).

El-Semary, M.A., Kaahwa, Y. and Rogers, J.S., Solid State
Commun. 12, 593 (1973).

Esaki, L. and Stiles, P.J., Phys. Rev. Lett. 14, 902
(1965).

Esaki, L., Stiles, P.J. and Chang, L.L., Phys. Rev. Lett.
20, 1108 (1968a).

Esaki, L., Chang, L.L., Stiles, J.P., O'Kane, D.F. and
Wiser, Nathan, Phys. Rev. 167, 637 (1968b).

Eschbach, H.L. and Kruidhof, W.E., Vacuum Microbalance Techn. 3, 207 (1965).

Fal'kovskij, L.A., Sov. Phys. Uspekhi, 1, (1968).

Fisher, J.C. and Giaver, I., J. Appl. Phys. 32, 172 (1961).

Frenkel, J., Phys. Rev. 36, 1604 (1930).

Gadzuk, J.W., J. Appl. Phys. 41, 286 (1970).

Gadzuk, J.W. and Lucas, A.A., Phys. Rev. B 7, 4470 (1973).

Garcia, N., Kao, Y.H., and Strongin, Myron, Phys. Rev. 5, 2029 (1972).

Geiger, A.L., Chandrasekhar, B.S. and Adler, J.G., Phys. Rev. 188, 1130 (1969).

Giaver, I., and Zeller, H.R., Phys. Rev. Lett. 20, 1540 (1968a).

Giaver, I. and Zeller, H.R., Phys. Rev. Lett. 21, 1385 (1968b)

Gogadze, D.G.A. and Kulik, I.O., Sov. Phys. Sol. State 7, 345 (1965).

Goy, P. and Castaing, B., Phys. Rev. B 7, 4409 (1973).

Gupta, N.M. and Upadhyaya, U.N., Phys. Rev. B 4, 2765 (1971).

Hapase, M.G., Tare, V.B. and Biswas, A.B., Acta Metallurgica 15, 131 (1967).

Harrison, W.A., Phys. Rev. 123, 85 (1961).

Hartman, T.E., J. Vacuum Tech. 3, 28 (1965).

Hauser, J.J. and Testardi, L.R., Phys. Rev. Lett. 20, 12 (1968).

Holland, L., in Vacuum Deposition of Thin Films (Chapman and Hall Ltd., 1961) pp. 74-78.

Hurault, J.P., J. de Physique 32, 421 (1971).

Jacklevic, R.C. and Lambe, J., Phys. Rev. Lett. 17, 1139 (1966).

Jacklevic, R.C. and Lambe, J., Mikkor, M. and Vassell, W.C., Phys. Rev. Lett. 26, 88 (1971).

Jacklevic, R.C. and Lambe, J., Mikkor, M. and Vassell, W.C., Solid State Commun. 10, 199 (1972).

Josefowicz, J. and Smith, H.J.T., Can. J. Phys. 51, 597 (1973).

Klein, J. Léger, A., Belin, M., DéForneau, D. and Sangster, M.J.L., Phys. Rev. 7, 2336 (1973).

Komnik, F. Yu. and Bukhstab, E.I., Sov. Phys. JETP 27, 34 (1968).

Komnik, F. Yu. and Pilipenko, V.V., Sov. Phys. Cryst. 16, 352 (1971).

Korneev, D.N., Lutskii, V.N. and Elinson, M.I., Sov. Phys. Solid State 12, 1049 (1970).

Kotov, B.A., Okuneva, N.M. and Plachenova, E.L., Sov. Phys. Solid State 11, 1615 (1970).

Kümmel, R., Zeitschrift für Physik 213, 282 (1968).

Larson, D.C., in Physics of Thin Films, ed. by Francombe, Hoffman (Academic Press, New York, 1971), pp. 137-143.

Lutskii, V.N., Korneev, D.N. and Elinson, M.I., Sov. Phys. JETP 4, 179 (1966).

- Lythall, D.J. and Wyatt, A.F.G., Phys. Rev. Lett. 20, 1361 (1968).
- Maissel, L.I., and Glang, R., in Handbook of Thin Film Technology (McGraw-Hill, 1970) pp. 14-18.
- Miles, J.L. and Smith, P.H., J. Appl. Phys. 34, 2109 (1963).
- Parker, G.H. and Mead, C.A., Phys. Rev. 184, 780 (1969).
- Penley, C., Phys. Rev. 128, 596 (1962).
- Pollack, S.R. and Morris, C.E., J. Appl. Phys. 35, 1503 (1964).
- Rowell, J.M. and Shen, L.Y.L., Phys. Rev. Lett. 17, 15 (1966).
- Rowell, J.M., J. Appl. Phys. 40, 1211 (1969).
- Rowell, J.M., McMillan, W.L. and Feldman, W.L., Phys. Rev. 180, 658 (1969).
- Sasaki, Y., J. Phys. Chem. Solids 12, 177 (1960).
- Sawatari, Y. and Arai, M., Jap. J. Appl. Phys. 7, 560 (1968).
- Schmidlin, F.W., J. Appl. Phys. 37, 2823 (1966).
- Shen, L.Y.L., Phys. Rev. Lett. 21, 361 (1968).
- Simmons, J.G., J. Appl. Phys. 34, 1973 (1963a).
- Simmons, J.G., J. Appl. Phys. 34, 2581 (1963b).
- Sommerfeld, A. and Bethe, H.A., in Handbuch der Physik, S. Flugge ed. (Springer-Verlag, Berlin, 1933), Vol. 24, p.150.
- Sommers, H.S., Rev. Sci. Instrum. 25, 793 (1954).

Steckelmacher, W., in Thin Film Microelectronics ed. by Holland, L. (John Wiley & Sons, New York, 1965), p.193.

Stevenson, R.J. and Hensley, E.B., J. Appl. Phys. 32, 1661 (1961).

Stockbridge, C.D., in Vacuum Microbalance Techniques, ed. by Behrndt, K. (Plenum Press, New York, 1966), vol. 5, p.193.

Stratton, R., J. Phys. Chem. Solids 23, 1177 (1962).

Tavger, B.A. and Demikhovskij, V. Ya., Sov. Phys. Uspekhi 11, 644 (1969).

Teshima, R., Private communication (1974).

Thornber, K.K., McGill, T.C. and Mead, C.A., J. Appl Phys. 38, 2384 (1967).

Tolansky, S., in Surface Microtopography (Longmans Green and Co., Ltd., 1960).

Trofimenkoff, P.N., Kreuzer, H.J., Wattamaniuk, W.J. and Adler, J.G., Phys. Rev. Lett. 29, 597 (1972).

Truell, R., Elbaum, C. and Chieck, B.B., Ultrasonic Methods in Solid State Physics (Academic Press, New York, 1969) pp. 290-294.

Tsui, D.C., Phys. Rev. Lett. 22, 293 (1969).

Tsui, D.C., Dietz, R.E. and Walker, L.R., Phys. Rev. Lett. 27, 1729 (1971).

Turner, P.S., Private communication (1974).

Vaisnys, J.R., McWhan, D.B. and Rowell, J.M., J. Appl. Phys. 40, 2623 (1969).

Vrba, J., Tunneling into Weakly Coupled Films of Al and Sn in Proximity (Ph.D. thesis, University of Alberta, 1971).

Wattamaniuk, W.J., Nonequilibrium Effects in Tunnel Junctions (Ph.D. thesis, University of Alberta, 1973).

Wilkins, J.W., Lecture notes on; Observable Many-Body Effects in Metals (Nordita, 1968).

Wolf, E.L., Nonsuperconducting Electron Tunneling (Academic Press, to be published, 1974).

Wyatt, A.F.G., Phys. Rev. Lett. 13, 401 (1964).

Yanson, I.K., Verkin, B.I., Ostrovskii, L.I., Teplitskii, A.B. and Skhlyarevskii, O.I., ZhETF. Pis. Red. 14, 40 (1971).

Zeller, H.R. and Giaver, I., Phys. Rev. 181, 789 (1969).

High Resolution Electron Tunneling Spectroscopy*

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A system which is capable of resolving changes in a tunneling junction conductance σ of about one part in 10^5 as well as providing *calibrated* values of $d\sigma/dV$ is described. Methods of simultaneous analog and digital recording on magnetic tape suitable for subsequent computer analysis are given. The flow chart for the computer programming is also presented along with a typical result.

INTRODUCTION

ELECTRON tunneling experiments have been very valuable in obtaining detailed information about the interactions giving rise to superconductivity.^{1,2} More recently, this technique has been applied to the study of inelastic excitations owing to phonons and molecular vibrations in metal-insulator-metal (M-I-M) tunnel junctions in which both metals are normal.²⁻⁷ The quantities of interest in these studies are the dynamic conductance $\sigma = dI/dV$ of the junction, and its derivative $d\sigma/dV = d^2I/dV^2$ as a function of junction bias voltage V .

This paper describes instrumentation capable of providing measurements of σ and $d\sigma/dV$ and recording these on magnetic tape suitable for subsequent computer analysis. The system is capable of resolving changes in σ of about one part in 10^5 as well as providing calibrated values of $d\sigma/dV$. The method of measurement employs a combination of harmonic detection and bridge techniques similar to that described earlier by Adler and Jackson⁸ (henceforth referred to as I) along with a data acquisition system which outputs the data on digital magnetic tape. The method of calibrating $d\sigma/dV$ with the aid of a digital computer is also discussed.

The paper is divided into three parts and an Appendix. Following this introduction, Sec I describes the circuit layout and discusses the bridge, sweep, and modulation circuit inasmuch as these differ from those described earlier in I. The digital recording formatting and buffering are also discussed. Section II deals with the calibration of σ and $d\sigma/dV$ and develops an integral equation scheme whereby $d\sigma/dV$ may be calibrated in absolute terms. A flow chart for computer programming of this calibration is also given. The final section summarizes the operating procedure and gives typical results. At the end of the paper there is an Appendix which deals briefly with the errors which can occur owing to excessive harmonic distortion in the modulation supply.

I. THE CIRCUITRY

The analog part of the circuitry described in this section is an outgrowth of the bridge described in I and we will consider here only those aspects of the bridge not previously discussed. Figure 1 shows a schematic of the bridge

enclosed in a rectangle of dashed lines. This bridge differs from the earlier version in the following ways.

(1) A variable capacitance C_d (100 nF in steps of 0.1 nF) has been added to compensate for the junction and stray capacitance.

(2) The output of the bridge is now transformer coupled to the preamplifier (Triad G-10 transformer). This transformer is preceded by 20 μ F polystyrene capacitors to prevent the possibility of direct current altering the transformer core hysteretically.

The bridge arms R are chosen so that $R \gg R_T$, where R_T is the junction resistance. The sweep and modulation signal circuits are shown in Fig. 2. If the current modulation across the junction is given by $\delta \cos \omega t$, where δ is a small constant current amplitude, then from I we can write the voltage output across the transformer at angular frequency ω as

$$V_\omega = (\delta/\beta)[R_d - (dV/dI)_{I_0}] \cos \omega t \dots, \quad (1)$$

where $(dV/dI)_{I_0}$ is the dynamic resistance of the junction biased by a current I_0 . The factor β has the form $1 + R_d/R + 2R_d/Z$ where Z is the transformer impedance. The modulation level is kept low so that the instrumental smearing is of the order of the thermal smearing (kT at 1 K is 86 μ V rms). Since we work primarily at liquid helium temperatures the signal levels are very low so the bridge has to be well shielded and leads kept short. The second harmonic at the transformer will be given by

$$V_{2\omega} \propto \frac{1}{4} \delta^2 (d^2V/dI^2)_{I_0} \cos 2\omega t \dots \quad (2)$$

Since the bridge is operated keeping a constant current through the junction ($R \gg R_T$) the measurements are restricted to junctions where V is single valued as a function of current I . That is, negative resistance regions such as those which occur in M-I-M junctions in which both metals are superconducting below 2 mV cannot be handled by this circuitry. Such negative resistance regions can however be measured by other methods.^{8,9} Errors owing to small amounts of harmonic distortion in the modulation supply can be serious if the bridge is operated far off balance (very nonlinear junctions); these are discussed in the Appendix and the above bridge equations are re-derived considering a small component of second harmonic present.

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We turn our attention now to the analog and digital recording of the data. The bridge signal is amplified by a PAR type 113 preamplifier followed by a PAR model 122 lock-in amplifier, whose dc output is fed to the Y axis of a Hewlett-Packard model 7001 X-Y plotter. The Triad G-10 transformer between the bridge and preamplifier is used with junctions having a resistance of $200\ \Omega$ or less at $1000\ \text{Hz}$. The bridge and analog recording system functions in the same way as that described in I with a slightly better signal-to-noise ratio. The modulation supply (Fig. 2) is essentially that described in I. The sweep circuit (Fig. 2) is similar to that in I but has been changed so that to allow convenient positive-, negative-, or center-zero sweeps to be executed. The sweep is provided by a motor drive to one of the $2\ \text{k}\Omega$ (10 turn) potentiometers in the circuit. Using a reference frequency of $1000\ \text{Hz}$ the recorder plots a signal proportional to dV/dI as a function of junction bias V . With a reference frequency of $2000\ \text{Hz}$, d^2V/dI^2 is plotted as a function of V . The system is arranged in such a way that analog and digital recordings are made simultaneously.

The analog-to-digital conversion is accomplished with a Vidar 5203 data acquisition system; however, other similar systems, or components as outlined below can be used. With current prices dropping one can duplicate the functions shown in the blocks (Fig. 1) at somewhat lower cost. We now describe the digital part of the system. Our system has a 10-channel reed relay scanner (Vidar 604). The scanner is arranged so that the signal from the lock-in amplifier, our dependent variable proportional to dV/dI or d^2V/dI^2 , is fed to channels 2-5 and 7-10 in parallel. The junction bias voltage is our independent variable and it is fed through a buffer amplifier (Hewlett-Packard 2470A) to channels 1 and 6 of the scanner. Since the scanner operates in a continuously cyclic mode and the

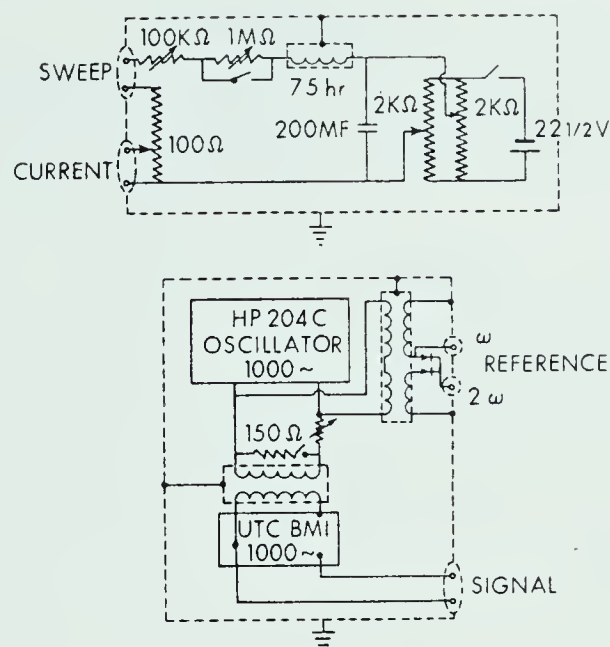


FIG. 2. The sweep circuit and the modulation supply.

sweep progresses in time, we obtain a value of bias voltage V by averaging channels 1 and 6. The corresponding dependent variable (dV/dI or d^2V/dI^2) is obtained by averaging the output of channels 2-5. The next pair of points is obtained by forming V from an average of channels 6 and 1 and the dependent variable by averaging channels 7-10, etc. One can, of course, use only two channels for the recording, but we have been using this averaging procedure because transient noise from other abs in the building is sometimes troublesome. The scanner signal is fed to an integrating digital voltmeter (Vidar 521). This IDVM is usually operated with a 166 msec integration time which provides a resolution of one part in 10^5 . The coupler (Vidar 653-03) provides the interface between the IDVM and the 7-track BCD coded tape, it also provides the requisite command signals for the scanner and voltmeter to read the data sequentially. Again the recording and interfacing can be done with other components; in fact 9-track tape and a less redundant coding could be used.

The absolute calibration of the conductance is accomplished by replacing the tunnel junction with a precision decade resistance and recording the lock-in output for about 15 resistance values spanning the resistance variation of the junction. The data are recorded on four separate files on the tape to allow ease of computer handling. The first file contains nominally 2000 pairs of points pertaining to the bias voltage and the uncalibrated conductance (lock-in output). The next file contains 15 pairs of calibration points for calibrating the conductance. The third file contains about 4000 uncalibrated d^2V/dI^2 points and their respective bias voltages. The fourth file contains the zero level for the calibration of the second derivative. This is obtained by recording the lock-in output level (lock-in tuned to $2000\ \text{Hz}$) when no harmonic ($2000\ \text{Hz}$) signal is present.

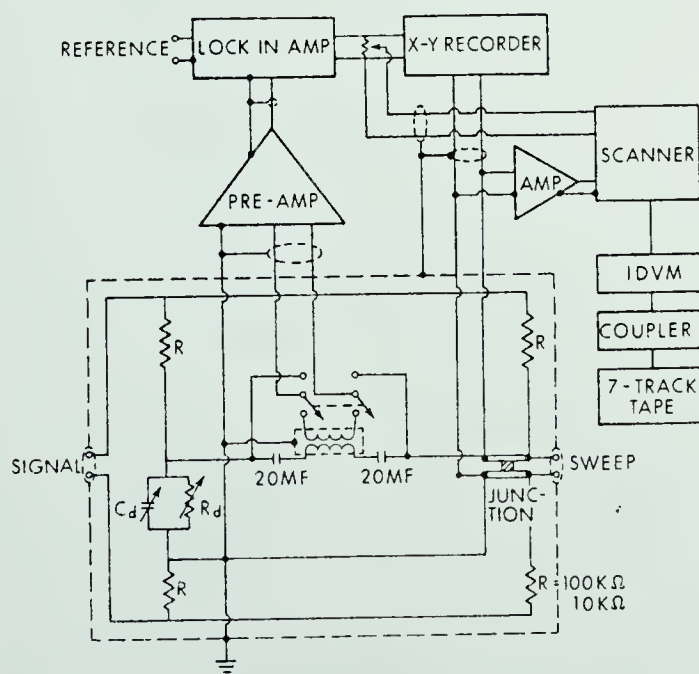


FIG. 1. The bridge circuit.

II. CALIBRATION

In this section we describe the basic calibration scheme used to obtain values of σ and $d\sigma/dV$. The actual procedure and flow chart for programming of this information are given at the end of this section.

A. Conductance (σ) Calibration

Let the lock-in output at the fundamental frequency be denoted as y_1 . Then as shown in I the junction dynamic resistance dV/dI is related to y_1 in accordance with Eq. (1). The first file on the magnetic tape is a collection of 2000 points (V, y_1) and thus contains the necessary information to obtain a plot of σ as a function of V if we know the calibration of y_1 in terms of a known set of resistance values R . This information is recorded on the second file and because the bridge response is linear we can obtain m and b for

$$\sigma = dI/dV = (my_1 + b)^{-1}, \quad (3)$$

from these data, thus obtaining a calibrated conductance plot (σ as a function of V).

B. Second Derivative ($d\sigma/dV$) Calibration

Denoting the second harmonic output of the lock-in as y_2 we have from I

$$d\sigma/dV = d^2I/dV^2 = \eta\sigma^3(V)y_2(V), \quad (4)$$

where $y_2(V) \propto d^2V/dI^2$.

Because of small amounts of second harmonic distortion present in the modulation supply (0.01%), we cannot treat η as a constant (see Appendix) so we will write $\eta = \eta(V)$. We can then proceed to determine $\eta(V)$ from $\sigma(V)$ and $y_2(V)$ using the integral equation

$$\sigma(V) - \sigma(V_a) = \int_{V_a}^V \eta(x)\sigma^3(x)y_2(x)dx, \quad (5)$$

where V_a is any particular value of bias voltage. We now write Eq. (5) in an operator equation form,

$$\hat{A}u = f, \quad (6)$$

where

$$f(V) = \sigma(V) - \sigma(V_a). \quad (7)$$

If Eq. (6) is solvable, then the solution η will minimize the functional

$$F(u) = \|\hat{A}u - f\|^2 = \int_{V_a}^V (\hat{A}u - f)^2 dx. \quad (8)$$

The replacement of Eq. (6) by the variational problem of minimizing the functional $F(u)$ is essentially a least squares technique.¹⁰ We can expand

$$u_n = \sum_{k=1}^n a_k \psi_k, \quad (9)$$

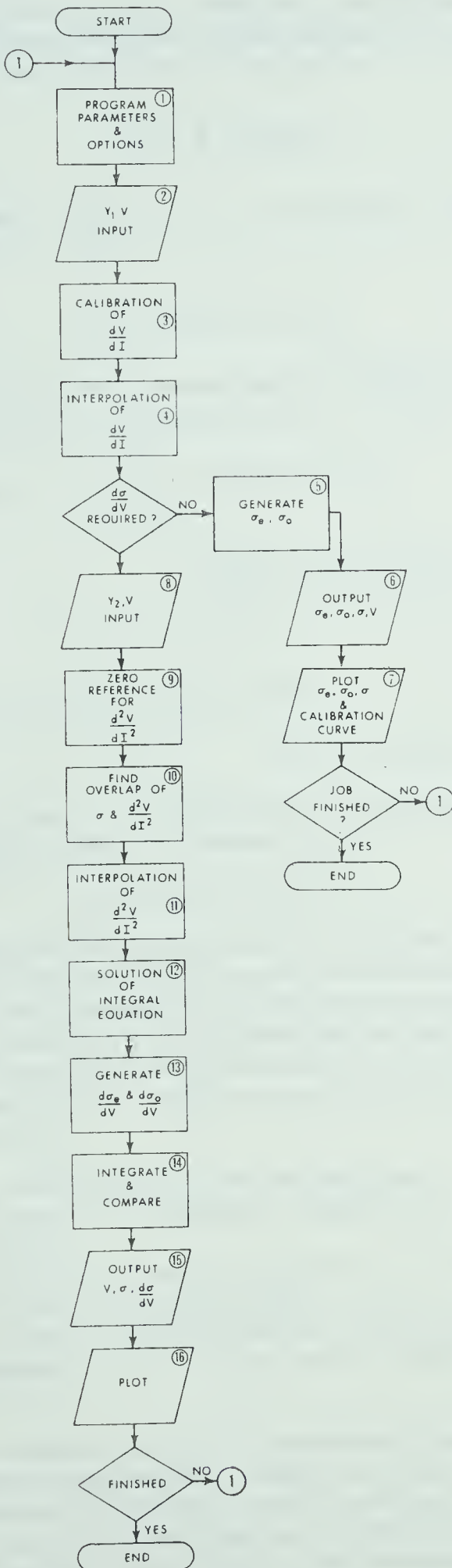


FIG. 3. The flow chart for the complete computer program.

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and choose the expansion coefficients a_k so that $\|\hat{A}u_n - f\|^2$ is a minimum. Using the standard notation for the scalar product of two functions $f(x)$ and $g(x)$ as

$$(f, g) = \int f(x)g(x)dx, \quad (10)$$

we obtain a system of n linear algebraic equations ($i=1, 2, \dots, n$),

$$\sum_{k=1}^n a_k (\hat{A}\psi_k, \hat{A}\psi_i) = (\hat{A}\psi_i, f). \quad (11)$$

Equations (5) and (6) can now be put in this format choosing the set $\{\psi_k\}$ in polynomial form $\psi_k = x^{k-1}$. Then

$$(\hat{A}x^{k-1}, \hat{A}x^{i-1}) = \int_{V_a}^V \left[\int_{V_a}^z \sigma^3(\mu) \gamma_2(\mu) \mu^{k-1} d\mu \right] \times \left[\int_{V_a}^z \sigma^3(\nu) \gamma_2(\nu) \nu^{i-1} d\nu \right] dz \quad (12)$$

and

$$(\hat{A}x^{i-1}, f) = \int_{V_a}^V \left[\int_{V_a}^z \sigma^3(\nu) \gamma_2(\nu) \nu^{i-1} d\nu \right] \times [\sigma(z) - \sigma(V_a)] dz, \quad (13)$$

where $i, k=1, 2, \dots, n$. In this way one can solve Eq. (11) and obtain a polynomial solution for $\eta(V)$

$$\eta(V) = a_1 + a_2 V + a_3 V^2 + \dots \quad (14)$$

One finds in practice that a quadratic form for η is sufficient to determine absolute values of η to a few parts in 10^3 .

We now outline the programming scheme to implement the above method. Figure 3 shows a flow chart for the computer programming. Program parameters and options are specified in block 1. These parameters include the following information:

- (i) number of files to be read on input tape;
- (ii) range of the independent variable, V (e.g., -300 to $+300$ mV);
- (iii) interval of V used in output data (e.g., a point at every 0.2 mV voltage change); and
- (iv) resistance calibration data, i.e., values of resistance corresponding to the V_1 values used in calibration (see Sec. II.A).

The available options include a specification of which and how many of the dependent variables are to be calculated and plotted. The plotting is done by generating a 7-track BCD tape which then is used to make off-line plots on a Calcomp plotter. Since in some of our measurements we are interested in inelastic processes which occur in tunnel junctions and these are even functions of bias voltage V ,

it is convenient to separate σ and $d\sigma/dV$ into its even and odd parts,

$$\sigma_e(V) = \frac{1}{2}[\sigma(V) + \sigma(-V)] \quad (15)$$

$$\sigma_o(V) = \frac{1}{2}[\sigma(V) - \sigma(-V)]. \quad (16)$$

Furthermore, it is sometimes convenient to reduce these functions to dimensionless quantities independent of actual junction resistance, in order to facilitate intercomparison of junctions. We achieve this by arbitrarily normalizing the junction conductance by dividing it by its value at zero bias, i.e., $\gamma = \sigma(V)/\sigma(0)$. Thus in block 1 we choose from the following dependent variables: $\sigma, \sigma_e, \sigma_o, \gamma, \gamma_e, \gamma_o, d\sigma/dV, d\sigma_e/dV, d\sigma_o/dV, d\gamma/dV, d\gamma_e/dV, d\gamma_o/dV$.

Block 2 in Fig. 3 shows the conductance data input (file 1 on data tape). Block 3 (file 2 on data tape) includes the input data for calibration and calculates m and b in Eq. (3). The deviations from linearity are also calculated and an optional plot can also be made. Since in practice with a digital computer calculations are made on a fixed grid, i.e., equal spacing of independent variable, the 2000 or so points (V, Y_1) are reduced to about 500 points at fixed voltage intervals (say 0.2 mV). This procedure is represented by block 4 along with a calculation of the corresponding (V, σ) points using Eq. (3). Blocks 5-7

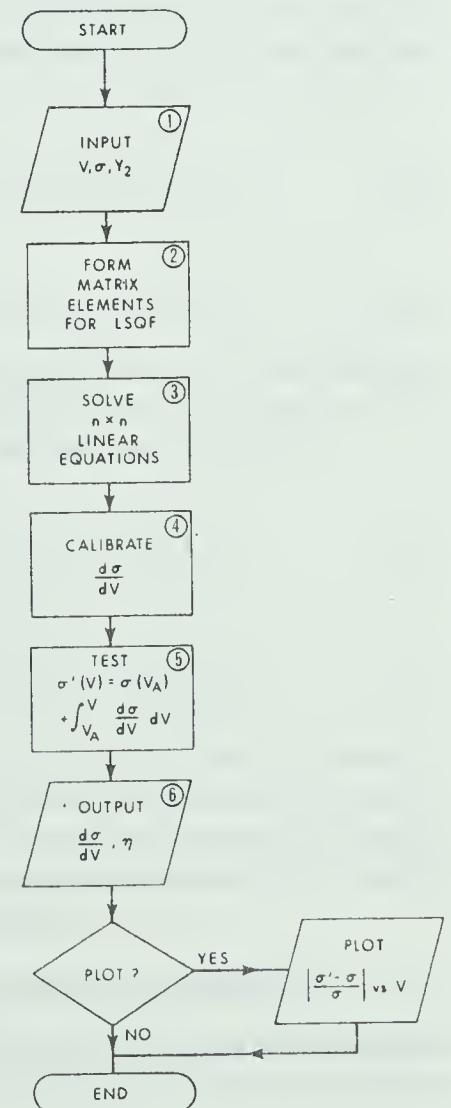


FIG. 4. The flow chart for the integral equation [Eq. (5)] subroutine.

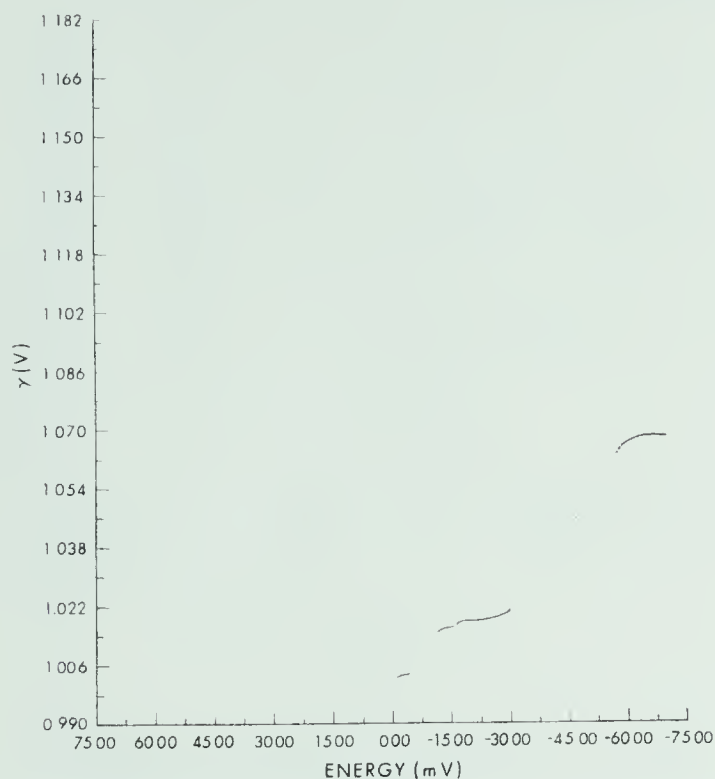


FIG. 5. The junction conductance, normalized by the conductance at zero bias, of a Pb-insulator-Pb junction at 1.05 K with 8 kOe field.

separate the conductance into odd and even parts and calculate the required junctions and produce the plotting tape.

We now turn our attention to the calculation of absolute values of $d\sigma/dV$. The 4000 or so pairs of points (V, Y_2) (file 3) and the zero level (file 4, described Sec. I) are the inputs in block 8. Block 9 compares this to the zero level obtained by calculating the location of a minimum in the $\sigma(V)$ points from the previous calculations. This provides a self-consistency check for those junctions which have conductance minima. In order to carry out a solution of the integral equation (5) we have to insure that we have V_2 values at the same voltage points for which we have conductance values. This overlap and interpolation

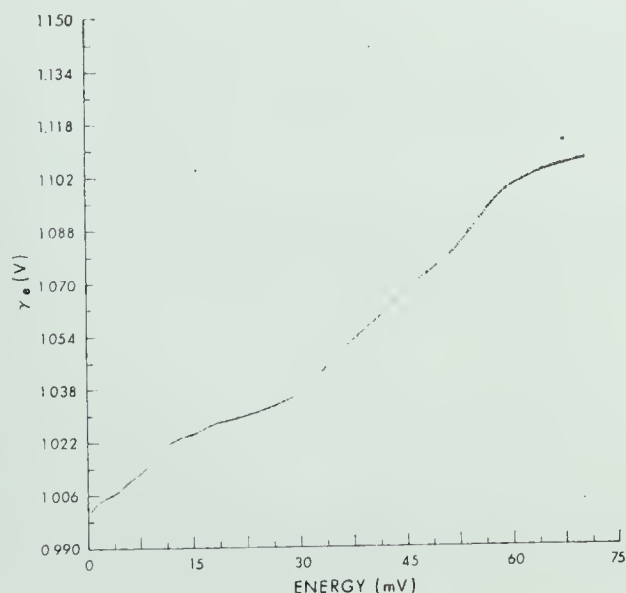


FIG. 6. The even part of the conductance of the junction shown in Fig. 5.

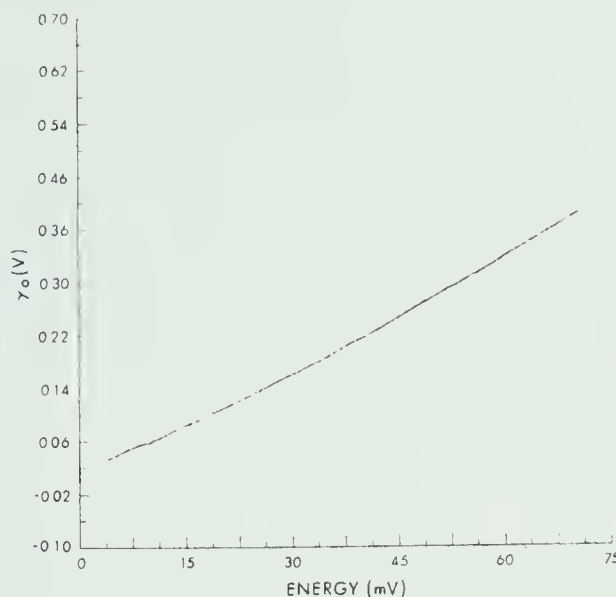


FIG. 7. The odd part of the conductance of the junction shown in Fig. 5.

function is achieved in blocks 10 and 11. The solution of the integral equation (block 12) is shown in more detail in Fig. 4. Following the input of data the matrix elements are calculated in block 2 with $n=3$ (larger values of n have not been required for our junctions). A solution of this system of three linear equations in three unknowns provides us with the three coefficients a_1, a_2, a_3 of Eq. (14). In practice η is calculated separately for positive and negative voltages. The rest of the calculations calibrate $d\sigma/dV$ by Eq. (4) and perform a check by calculating

$$\sigma'(V) = \sigma(V_A) + \int_{V_A}^V \frac{d\sigma}{dV} dV \quad (17)$$

and

$$\epsilon(V) = [\sigma'(V) - \sigma(V)] / \sigma(V) \quad (18)$$

for all the 500 or so values of V used. ϵ is always within a few parts in 10^5 (see Appendix). Returning now to Fig. 3, block 13 calculates odd and even parts of $d\sigma/dV$

$$\frac{d\sigma_e}{dV} = \frac{1}{2} \left[\left(\frac{d\sigma}{dV} \right)_V - \left(\frac{d\sigma}{dV} \right)_{-V} \right] \quad (19)$$

$$\frac{d\sigma_o}{dV} = \frac{1}{2} \left[\left(\frac{d\sigma}{dV} \right)_V + \left(\frac{d\sigma}{dV} \right)_{-V} \right]. \quad (20)$$

As a double check, $d\sigma_e/dV$ and $d\sigma_o/dV$ are integrated by Eq. (17) and compared to the values of σ_e and σ_o obtained directly (block 5); again the discrepancy is only a few parts in 10^5 . The rest of the program simply outputs the rest of the data and plots.

III. OPERATION AND RESULTS

The bridge is balanced at some value of bias within the sweep range in such a way that the full dynamic range

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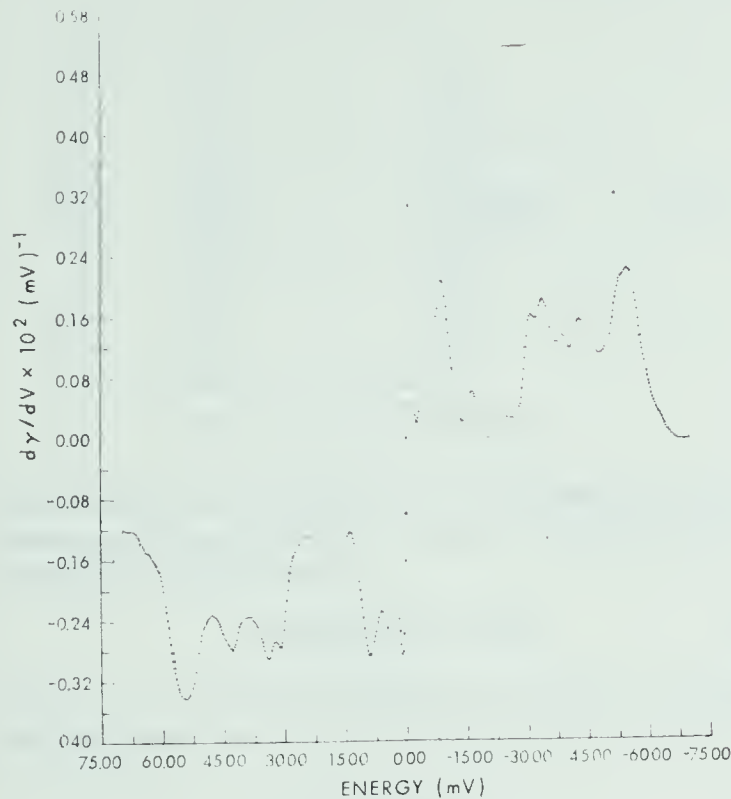


FIG. 8. The derivative of the conductance, normalized by the conductance at zero bias, of the junction shown in Fig. 5.

of the lock-in amplifier (tuned to 1000 Hz) is employed in the process of sweeping. The capacitance C_d is adjusted to compensate for the junction and stray capacitance. The sweep is then initiated and analog and digital recording is carried out simultaneously. Following completion of the sweep, an end of file mark is placed on the tape. The junction is now replaced by a decade resistance, C_d

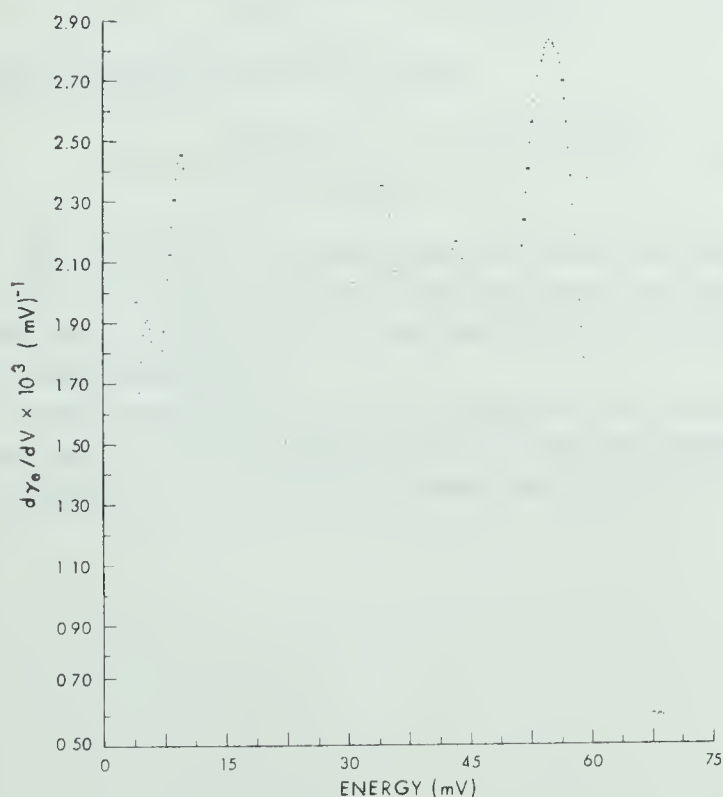


FIG. 9. The even part of the derivative of the conductance of the junction shown in Fig. 5.

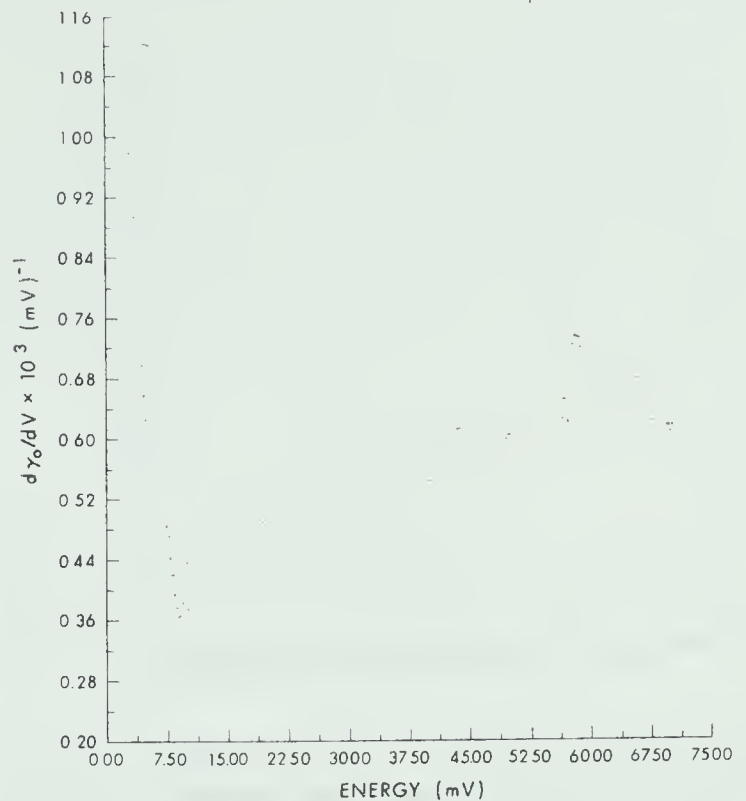


FIG. 10. The odd part of the derivative of the conductance of the junction shown in Fig. 5.

is removed, and calibration points are recorded on the second file. Typical results for a Pb-insulator-Pb junction are shown in Figs. 5-7. These were measured at 1.05 K with an 8 kOe field to keep the Pb from becoming superconducting. The second derivative measurements are carried out by retuning the lock-in to 2000 Hz while the bridge is still fed with the 1000 Hz signal. Simultaneous analog and digital recording is again carried out, the digital recording being placed in the third file of the tape. Following the completion of the sweep the lock-in amplifier is shorted at the input and its output voltage is recorded in the fourth file to provide the zero level reference. Typical results are shown in Figs. 8-10.

This system has now been in operation for about two years and is found to be simple and convenient to operate. The data shown in the figures were obtained by recording about 2000 first derivative points and 4000 second derivative points. The output plots for γ and $d\gamma/dV$ (Figs. 5 and 8) contain 1000 points while the remaining odd and even plots have 500 points. The computing time required was 2 min on an IBM 360-67 computer, using Fortran H. The off-line plotting time for these plots requires about 15 min.

We wish to thank Dr. J. S. Rogers for many useful discussions during the course of this work.

APPENDIX: EFFECT OF HARMONIC DISTORTION

Consider the simplified bridge in Fig. 11. Let the modulation frequency be ω and allow for a small fraction, x , of

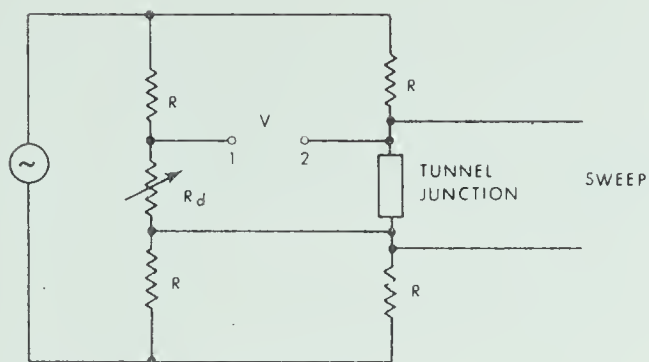


FIG. 11. Simplified bridge circuit.

second harmonic distortion. We will neglect higher harmonics in this analysis. We can then describe the current modulation through R_d as

$$I_m = \delta(\cos\omega t + x \cos 2\omega t). \quad (A1)$$

Note x is a very small fraction in our bridge $x \sim 0.0001$. Let the tunnel have a dynamic conductance $\sigma_T = (dI/dV)$ and define

$$\Gamma(V) = R_d \sigma(V) - 1 \quad (A2)$$

$$\Gamma'(V) = R_d d\sigma/dV, \quad (A3)$$

then at balance we have $\Gamma = 0$.

For simplicity we denote the modulation voltage amplitude across R_d as

$$\psi_d = R_d \delta. \quad (A4)$$

Then the lock-in output at the fundamental frequency will be

$$V_{1\omega} \propto \frac{\Gamma}{\Gamma+1} \psi_d \left[1 + x \frac{\psi_d}{2} \frac{\Gamma'}{\Gamma(\Gamma+1)^2} \right]. \quad (A5)$$

The second harmonic output will be

$$V_{2\omega} \propto -\left(\frac{\psi_d}{2}\right)^2 \frac{\Gamma'}{(\Gamma+1)^3} \left[1 - \frac{4x(\Gamma+1)^2}{\psi_d \Gamma'} \right]. \quad (A6)$$

We note that the fractional error in the first derivative increases linearly with increasing modulation level while the second derivative fractional error decreases with increasing modulation.

If the bridge is balanced and a linear element is put in the place of the junction ($d\sigma/dV = 0$), then the harmonic distortion has no effect since it cancels on both sides. In the

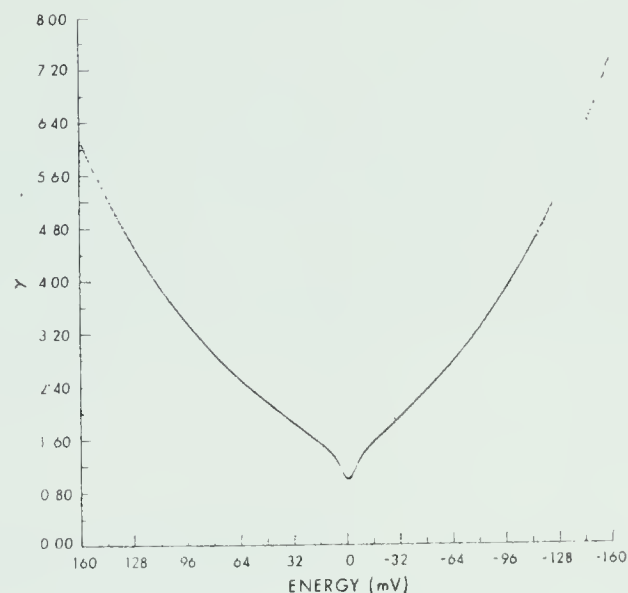


FIG. 12. The junction conductance, normalized by the conductance at zero bias, of a Co-CoO-In junction at 4.2 K.

case of a nonlinear element ($d\sigma/dV \neq 0$), however, the effect is to unbalance the bridge thereby preventing cancellation for the small distortion signal. This is the reason that η is not a constant and has the form given in Eq. (14). For the most part calibrating σ by substituting a resistance decade along with the computations outlined in Sec. II provides a good calibration with ϵ [Eq. (18)] kept to a few parts in 10^5 . Very nonlinear junctions such as Fig. 12 will give $\epsilon \sim 10^{-3}$. But for these junctions we carry out the recording piecewise so that R_d is readjusted various times in the sweep range to rebalance the bridge; in this way ϵ can again be reduced to a few parts in 10^5 .

* Supported in part by a grant from the National Research Council of Canada.

¹ W. L. McMillan and J. M. Rowell, *Treatise on Superconductivity*, edited by R. D. Parks (Marcel Dekker, New York, 1969).

² C. B. Duke, *Tunneling in Solids* (Academic, New York, 1969).

³ J. Lambe and R. C. Jacklevic, *Phys. Rev.* **165**, 821 (1968).

⁴ J. M. Rowell, W. L. McMillan, and W. L. Feldmann, *Phys. Rev.* **180**, 658 (1969).

⁵ A. L. Geiger, B. S. Chandrasekhar, and J. G. Adler, *Phys. Rev.* **188**, 1130 (1969).

⁶ J. G. Adler, *Phys. Lett.* **29A**, 675 (1969).

⁷ J. G. Adler, *Solid State Commun.* **7**, 1635 (1969).

⁸ J. G. Adler and J. E. Jackson, *Rev. Sci. Instrum.* **37**, 1049 (1966).

⁹ J. S. Rogers, *Rev. Sci. Instrum.* **41**, 1184 (1970).

¹⁰ S. G. Mikhlin and K. L. Smolitskiy, *Approximate Methods for Solution of Differential and Integral Equations* (American Elsevier, New York, 1967), pp. 224-226.

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SIZE EFFECT IN THE MAGNETIC FIELD DEPENDENCE OF NONEQUILIBRIUM ELECTRON TUNNELING*

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The electron bottleneck in normal metal-insulator-metal tunnel junctions due to nonequilibrium effects has been investigated in the presence of a magnetic field. The observed results are due to a new geometrical size effect and are explained in an extension of our nonequilibrium theory.

IT HAS recently been shown¹ that small conductance minima ($\sigma = dI/dV$) below the phonon structure observed in normal metal-insulator-metal junctions are due to the finite relaxation times of the tunneling electrons in the metals comprising the junction. States which would otherwise be available for tunneling are blocked creating an electron bottleneck. This nonequilibrium effect has been explained in detail in a transport model.

In the previous work,¹ superconductivity in the electrodes of the junction was quenched using a magnetic field. In this letter we report on a detailed study of the magnetic field dependence of the small Zero-Bias-Anomalies (ZBA) observed in such tunnel junctions. An explanation is given for the observed behavior as a size effect due to the finite geometry of the junction.

For a systematic study of magnetic field effects in tunnel junctions it is useful to think in terms of two possible field orientations: the longitudinal field which is parallel to the tunneling electron momentum thus providing no Lorentz force on the electron, and the transverse field which is perpendicular to the tunneling electron motion giving rise to a Lorentz force. Measurements on a number of junctions using different electrode metals (Al, Au, Mg, Pb, Bi) have shown *no* magnetic field dependence of the ZBA in *longitudinal* fields up to 70 KG (the highest field

available to us). This suggests that in the low energy region where the ZBA is observed no appreciable changes in the Fermi surface occur in our junctions that could affect the tunneling mechanism.² However, in a *transverse* field a dramatic field dependence is observed as is shown in Fig. 1(b) which gives a family of $\sigma(V)$ vs V curves as a function of magnetic induction B . For comparison Fig. 1(a) shows the temperature dependence of the same junction.³

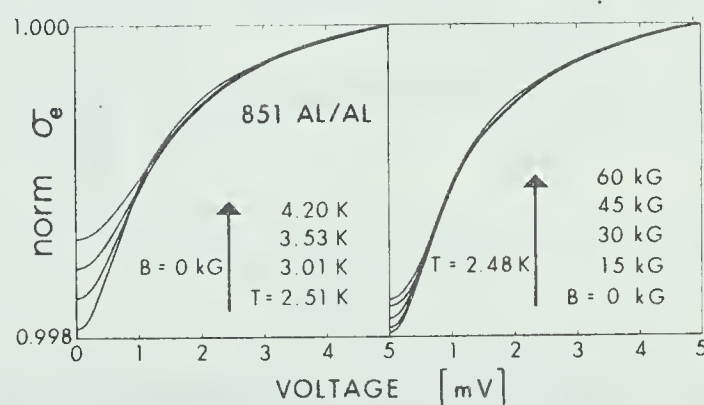


FIG. 1. Normalized even part of the conductance $\sigma_e(V)/\sigma_e(V=5 \text{ mV})$ vs V for an Al-Al junction (851 Å) for (a) different temperatures T and (b) various magnetic inductions B .

In our previous work¹ we have shown that the electron bottleneck arises from the competition of the tunneling rate D/τ_0 with the elastic scattering frequency τ_i^{-1} (e.g. impurity and diffuse boundary scattering) and the electron-phonon relaxation rate $\tau_{ep}^{-1}(\omega, T)$, the latter giving rise to the temperature dependence of the ZBA.

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To understand the magnetic field dependence we need not consider the electron-phonon interaction because as mentioned above Fermi-surface effects are of no consequence here. Furthermore, because the tunneling barrier is less than 50 Å thick the tunneling rate will be unaffected by the Lorentz force. However, the Lorentz force induced electron drift in the electrodes provides an additional mechanism to take electrons out of the forward direction thus expanding the bottleneck by providing more tunneling states in the electrodes. In the absence of a magnetic field specular scattering of electrons by the electrode boundaries will not be effective in relieving the bottleneck because such scattering does not remove electrons from the forward direction. In a transverse field, however, the specularly reflected electrons will drift along the electrodes. This provides an additional mechanism for the removal of electrons from the forward direction. In our transport model we can account for this drift by a relaxation time

$$\tau_d(B) = \frac{a}{v_{\text{drift}}} = \frac{a}{v_F} \frac{l}{R} \left[1 - \left(1 - \frac{l^2}{R^2} \right)^{1/2} \right]^{-1}$$

where a is the effective width of the junction in the direction of the drift, v_F is the Fermi velocity of the electron, l is the electrode thickness and $R = mv_F c / eB$. For $B \lesssim 60$ KG $R \gtrsim 20,000$ Å which is much larger than the electrode thickness used here ($l \lesssim 1000$ Å). Hence we can simplify, $\tau_d(B) \approx 2mc/e \cdot a/l \cdot B^{-1}$ and the total relaxation time in one electrode is given by $\tau^{-1} = \tau_i^{-1} + \tau_d^{-1}(B) + \tau_{ep}^{-1}(\omega, T)$.⁴ To simplify the discussion let us assume that the bottleneck is entirely due to one electrode only. (This can be achieved e.g. by using a second electrode with a strong electron-phonon interaction.) We then find for $T = 0$ K and assuming that the electron-phonon coupling is linear in ω ($\alpha^2 F = \alpha^2 \omega$) in the low energy region,

$$\sigma(V) \propto D \left[1 - \frac{D/\tau_0}{1/\tau_i + \frac{e}{2mc} \frac{l}{a} B + \frac{\pi}{\hbar} \alpha^2 (eV)^2} \right] \quad (1)$$

This shows that the effect of B is to reduce the ZBA by removing electrons from the forward direction. The rate at which this removal takes place for a given B depends entirely on the electrode geometry via the ratio l/a of the electrode thickness l to the effective width of the junction a . This size effect has been checked experimentally by varying the film thickness

l and by looking at crossed film junctions in which the width of base and top films were different, thus giving rise to a rectangular tunneling area of dimension $a_x \cdot a_y$ with $a_x \neq a_y$. It was found that a predictable change occurred according to equation (1) when the field was changed from the x -direction into the y -direction.

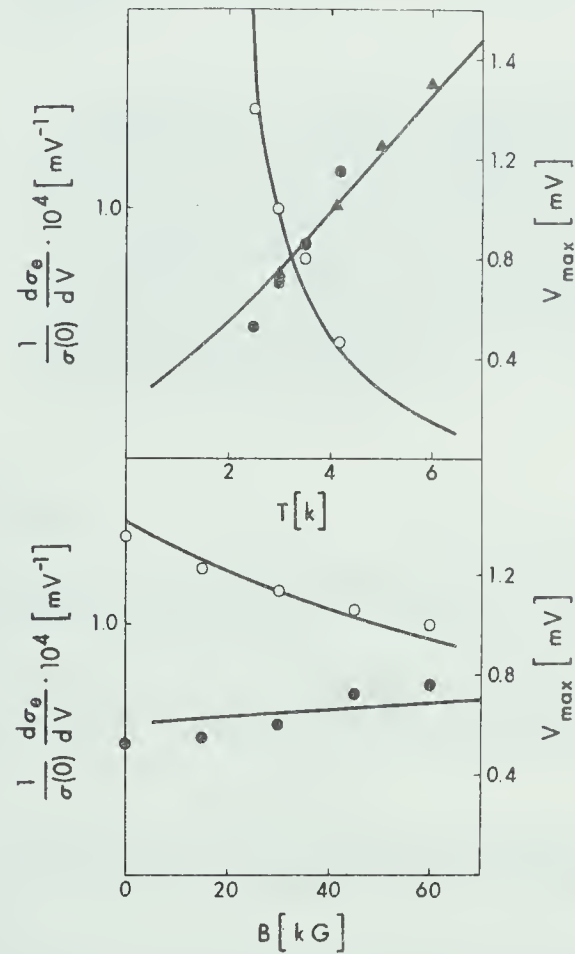


FIG. 2. (a) Peak heights (open circles) and peak positions (full dots) in the normalized derivatives of the even part of the conductance as a function of temperature for an Al-Al junction (851 Å); triangles; data for the 691 Å junction. (b) Peak heights and peak positions for the 851 Å junction as a function of magnetic induction B . Solid curves: theoretical results.

We have analysed quantitatively the data for an Al-Al junction. Fig. 2(a) shows the peak heights and peak positions in the normalized even derivative of $\sigma(V)$, i.e. $1/\sigma(0) \cdot d\sigma_e(V)/dV$ as a function of temperature. To show the reproducibility of our data, we have included in this graph data taken on a different junction a year ago.¹ (Note: A direct comparison of the two junctions can only be made for the peak positions which depend on τ_i and τ_{ep} alone. Without

renormalization a comparison of peak heights is not meaningful because the peak heights are proportional to the (geometry dependent) tunneling rate D/τ_0 which differed by about a factor of 5 for the two junctions due to slightly different resistances and much thinner Al films in the junction 851.) The elastic scattering time obtained from the theoretical curves is $\tau_i = 2.5 \cdot 10^{-10}$ sec assuming $\alpha^2 = 0.003/\text{meV}$ for Al.¹

To make a similar analysis for the field dependence we can use equation (1) for $T = 0\text{K}$ to obtain

$$\frac{1}{\sigma(0, B)} \frac{d\sigma(V_{\max}, B)}{dV} = \frac{1}{\sigma(0, 0)} \frac{d\sigma(V_{\max}, 0)}{dV} \left(1 + \frac{e\tau_i}{2mc} \frac{l}{a} B\right)^{-\frac{3}{2}} \quad (2)$$

$$V_{\max}(B) = V_{\max}(0) \left(1 + \frac{e\tau_i}{2mc} \frac{l}{a} B\right)^{1/2}$$

for the variation of the peak height and peak position in $d\sigma/dV$ as a function of B . It should be noted that equations (2) are, of course, only rigorously valid for

$T = 0\text{K}$. But at low enough constant temperature the B -dependence should be fairly accurately described. The theoretical curve in Fig. [2(b)] was obtained by using the value $\tau_i = 2.5 \times 10^{-10}$ sec from the temperature dependence and the geometrical data of our junction, namely $l = 680 \text{ \AA}$ and $a = 0.3 \text{ mm}$. This leads to a coefficient $5 \times 10^{-3}/\text{kG}$ in front of B in equations (2), which reproduces the data surprisingly well. It should be noted once more that the theoretical fit of the B -dependence is *parameter-free*. The quality of agreement might be viewed as fortuitous but certainly an order-of-magnitude agreement should always be possible.

In conclusion, the magnetic field dependence of the small ZBA in the transverse case has been explained in terms of a size effect due to the finite geometry of the tunneling junction.⁵ Moreover, the absence of any field effects on the ZBA in the longitudinal case has been understood and leads to a clear separation of the non-equilibrium effects at low bias from possible Fermi-surface effects.²

REFERENCES

1. ADLER J.G., KREUZER H.J., TROFIMENKOFF P.N. and WATTAMANIUK W.J., *LT 13*, Boulder, Colorado; TROFIMENKOFF P.N., KREUZER H.J., WATTAMANIUK W.J. and ADLER J.G., *Phys. Rev. Lett.* **29**, 597 (1972).
2. KULIK I.O. and GOGADZE G.A., *Soviet Phys. JETP* **17**, 361 (1963); see also DUKE C.B., *Tunneling in Solids, Solid State Physics, Suppl. 10* (Edited by SEITZ F., TURNBULL D. and EHRENREICH H), Academic Press, New York (1969).
3. We give here σ vs V to complement reference (1) in which $d\sigma/dV$ vs V was plotted.
4. An additional correction stemming from the fact that specular reflection decreases like $\cos^2 \theta$ as the angle of incidence θ measured from the normal to the boundary, increases, is only of the order 10^{-3} for fields up to 70 kG in our thin metal films and can thus be neglected.
5. JAKLEVIC R.C., LAMBE J., MIKKOR M. and VASSELL W.C., *Phys. Rev. Lett.* **26**, 88 (1971); in this reference the 'quantum box' size effect is investigated which is quite different from the size effect considered here which is connected with the electron trajectories.

Der Einfluss eines Magnetfeldes auf gewisse Transportphänomene beim Elektrontunneleffekt in Metall-Isolator-Metall Tunneldioden wird untersucht. Die Resultate werden als ein neuer geometrische Effekt gedeutet und in einer Erweiterung unserer Nichtgleichgewichtstheorie quantitativ erklärt.

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